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HYDRAULIC FILLING IN METAL MINES

By WILLIAM EWART LIGHTFOOT

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OUTLINE OF REPORT

ABSTRACT

"Hydraulic filling," or "sand filling," is a system by which the material needed to fill underground openings is supplied as a dense pulp. Commonly, mill-tailing is used. The resultant fill, after deposition and draining, is known as a "hydraulic fill." Such fills have been efficiently employed to: (a) provide immediate support of the working-face during stoping, (b) facilitate the recovery of pillars, (c) support access openings, (d) limit surface damage, (e) enable the mining of parallel, hanging-wall orebodies, (f) permit the extraction of ore under water-bearing formations, (g) stabilize old workings prior to re-entry, (h) reduce rock-burst hazard, (i) control and prevent mine fires, (j) seal off ground-water, and (k) alleviate stream pollution and tailing disposal problems.

These various uses of hydraulic-filling have been developed during the last 85 years. Used initially in 1864 to arrest surface subsidence, the system has since been applied successfully to meet specific ground-support problems, and in some mines, has made possible continued operation by contributing essential cost reductions.

Methods of handling mine-fill material derived from an external source include transportation of the material by hand, mechanical, pneumatic, and hydraulic means, or a combination of such methods. The hydraulic method has many advantages not found in the others, a significant advantage being the low compressibility of the material as compared to other mine-fill material. Slime content of the fill material is most important as a factor in the cementation and consolidation of the fill.

The techniques of hydraulic filling, which include preparation and transportation of the pulp, and underground practices in placing fills, vary from mine to mine to meet different conditions. Experiments prior to adoption of hydraulic filling at any one mine is advisable.

Formerly, the exceptional support inherent in a hydraulic fill was the chief reason for the use of hydraulic filling, but recently, experience proved that it is also an important means of reducing mining cost. This is especially true where labor is a large part of the cost of filling by an alternate method, or where timber requirements are greatly reduced, which is often the case in "cut-and-fill" or "square-set" mines.

Indirect benefits are probably as important as the direct benefits derived from hydraulic-filling, and few significant disadvantages exist.

INTRODUCTION

Much of the information presented here is from published sources, although some has been taken from unpublished reports. The remaining material represents data gathered during the author's employment at the Central Eureka and the Holden mines, and from observation and consultation during visits to several other mines that are using hydraulic filling. Some discrepancies between data incorporated herein and published data indicate modifications in the methods now being used. Recent information from some mines, particularly foreign ones, is not available.

Most of the significant features of hydraulic filling systems are mentioned, but comprehensive descriptions of particular operations is not attempted, nor are complete details of construction of equipment included.

Acknowledgments. Nearly all of the information presented in this report has as its source the men who pioneered hydraulic filling methods. The author deeply appreciates the hospitality, the helpfulness, and the kind personal interest shown by the men of the several mines and plants that were visited. They include: the staff of the Consolidated Mining and Smelting Company of Canada, Limited, at the Sullivan Mine and the Chapman Camp Concentrator, Kimberley, British Columbia; Mr. Paul M. Price, mining engineer, and the staff of the Chelan Division, Howe Sound Company, Holden, Washington; Mr. E. H. Syms, mine superintendent, and the staff of the Central Eureka Mining Company, Sutter Creek, California; Mr. Richard Krebs, mill superintendent, and Mr. J. C. O'Donnell, mine superintendent, at the New Brunswick Mine of the Idaho-Maryland Mines Corporation, Grass Valley, California; Mr. C. N. Kravig, assistant mine superintendent, Mr. N. Herz, chief metallurgist, Mr. Frank Howell, cyanide plant foreman, and the staff of the Homestake Mining Company, Lead, South Dakota; Mr. C. M. Mathews, fire foreman, Mr. Elmer Norris, assistant mine foreman, Emma mine; Mr. Wm. H. Trudeau, mine foreman, Tramway mine, and several others on the staff of the Anaconda Copper Mining Company, Butte, Montana; Mr. Rollin Farmin, superintendent, Mr. C. E. Sparks, general mine foreman, and the staff of the Dayrock mine, Day Mines Inc., Wallace, Idaho.

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Definition of Terms. **Hydraulic filling** is used to denote a system of filling. It includes the flushing of solids underground, the preparation of the pulp, the transportation of the pulp, the preparation of the underground excavation, the dewatering of the pulp, and the entire operation that is involved when a fill is placed. **Hydraulic fill** is fill that has been hydraulically placed. The material of which a hydraulic fill is composed is referred to generally as **fill material**.

Good descriptive terminology for the fill material is lacking, but the following arbitrary definitions are used in this report: **Fines** is used to denote material suitable for use in hydraulic filling. It indicates no particular size range, except that the particle size is small enough to be satisfactory. **Slimes** is used, except where noted expressly to the contrary, to denote all material that will pass a 200-mesh screen regardless of its physical-chemical character. This distinction is convenient, but does not mean that the quantities and relations of the very minute particles are not significant. They probably are, but data are not complete enough to be conclusive. In keeping with these definitions, **desliming** is used to mean a reduction in the amount of minus 200-mesh material.[1]

A **large fill** is a hydraulic fill of many hundreds or thousands of tons that is placed continuously or in batches of considerable volume. A **small fill** may aggregate several thousands of tons, but is placed a few hundred tons at a time so that the depth of fill is never great between periods of thorough dewatering. Tonnage is given in dry tons.

Bulkhead is used to indicate any of the various devices constructed to confine the fill material. **Filter-bulkhead** identifies bulkheads that are constructed so as to permit drainage from the fill to pass through the bulkhead.

Dewatering is separation of the water from the solids when the fill material is originally deposited and the drainage of the water from the fill.

Fill Material. Broken rock, including waste from development, is the material commonly used for mine filling. It is not generally suited to hydraulic methods although crushed rock has been deposited hydraulically in some European mines. Glacial material, to be satisfactory, must not contain large boulders; the ratio of fines must be high. All of the largest and most successful applications of hydraulic filling utilize a fill material of small particle size exclusively, usually below 10-mesh. This provides superior fill which requires less water than fill of larger size, and produces less pipe line wear.

Good fill materials are river sand, dune sand, granulated slag, or mill tailing. Mill tailing is obtained from operating mills or dumps. In addition clay, culm, finely crushed rock, ashes, decomposed rock, burnt slate, rock salt, flue dust, boiler ash, and washery waste have been used to a varying extent throughout the world, although not always in metal mines.

Methods of Filling. Any material used for stope filling not derived from the stope must be transported and distributed. Several methods are used in handling the material: by hand, mechanically, pneumatically, or hydraulically, or a combination of these.

Distribution of the fill material within the stope by hand is slow, costly, and results in a comparatively poor fill, especially in flat stopes.

[1] All screen sizes refer to the Tyler series.

Mechanical methods include the use of cars, trucks, barrows, scrapers, or conveyor belts to transport the material from the skip or wastepass to the stope or transfer-raise. Interference and low efficiency in the transportation of ore, men, and supplies and cost of labor and maintenance is sometimes considerable.

The same kinds of equipment are used for distribution of the fill material in the stopes. In Europe, centrifugal stowing machines have been used. They are said to be suitable for stowing in flat veins, but require considerable space and labor, are costly to maintain, and of small capacity.

Two systems of pneumatic transport are adaptable to mine filling: the high-pressure system, usually intermittent in operation, and the low-pressure system, usually continuous. The high-pressure system has a limited effective radius and is suited only to the distribution of material within the stope; the low pressure system has a greater radius and is suitable for the transportation of material for longer distances in the mine.

In the high-pressure system, a container is alternately charged with material and then discharged by the air at a pressure of 70 to 100 pounds per square inch. The volume of air required is relatively low, as is the capacity.

In the low-pressure system, the fill material is carried in a line in which a volume of air about 300 times the volume of material is flowing. Some rather long low-pressure lines have been used. Material as fine as mill tailing has apparently not been handled in low-pressure systems.

All pneumatic systems are extravagant in the use of power. In addition, extremely rapid pipe wear is common, and is said to have been excessive in the South African gold mines. In the German and British coal mines, where pneumatic methods are most used at present, replacement of pipelines due to wear is one of the largest expenses. The moisture content of the material supplied to a pneumatic system must be closely controlled.

Pneumatic systems can handle material of larger particle size than hydraulic systems; they do not introduce additional water into the mine, and can be used where it is necessary to deposit the material in locations above the elevation of the end of the pipeline. The dust produced can be overcome by the use of water sprays, although such sprays complicate the filling procedure. Pneumatic methods can produce a tighter fill against a nearly horizontal back than can most hydraulic filling methods; however, the advantage is questionable because the walls are not as well supported. A fill that is placed pneumatically is not as well compacted and over a period of time is observed to settle and compress more than a hydraulic fill.

Hydraulic systems are continuous from the surface to the stope. No rehandling of material is required. Filling by hydraulic methods is rapid and simple, requires little labor, involves a minimum of maintenance of equipment, permits filling in inaccessible parts of a mine, introduces no dust hazard, and does not interfere with underground traffic. A hydraulic-filling system requires only the installation of a preparation plant on the surface, apparatus for conveying the material underground, and the preparation of each stope for containing and dewatering the material.

Fills placed hydraulically are claimed to be the tightest possible kind of fill. Many laboratory experiments and observations on full-scale operations have demonstrated that hydraulic fills are the most resistant of any continuous support used in mining. This results in cheaper mining methods, reduced timber consumption, greater recovery of ore, and less dilution, as well as decreased development per ton of ore mined and less mine maintenance.

Material deposited hydraulically flows into the small fissures and cracks in the adjoining rock, and penetrates areas of broken rock or of matted timber and waste. Except where the upper limit of the stope is nearly horizontal or is very irregular, the material is tight against all of the confining walls. Low dips require more care during filling than do steep dips to assure tight filling and good drainage.

Among the problems imposed by the use of hydraulic methods are: pumping of the excess water to the surface, pressure at depth on the pipeline, wear on the pipeline, possible necessity of desliming the material, effects on ventilation, construction of suitable bulkheads, and provision for adequate drainage.

HISTORICAL REVIEW OF HYDRAULIC FILLING

Hydraulic filling is thought to have been first used in the anthracite region of Pennsylvania. It was originated by a Catholic priest in the city of Shenandoah in 1864, who, in the hope of saving his church from destruction by subsidence, prevailed upon the president of the Philadelphia and Reading Coal and Iron Company to slush the breaker waste and culm into the old mine workings beneath his church.[2]

In 1884 culm was flushed underground at a mine near Schuykill, Pennsylvania, to extinguish a fire after attempts at drowning it with large volumes of water had failed. In the following two or three years hydraulic filling was used in neighboring regions for sealing off or extinguishing mine fires, arresting squeezes and supporting the surface. By the 1890's hydraulic filling had become well established.

From these early applications the process of "silting," "flushing," or "slushing," as hydraulic filling is called in the coal mines, became an important part of coal mining methods, especially in the Pennsylvania anthracite fields, where it has been employed continuously. It is now used as an important aid in the conservation of coal reserves.

The technique of hydraulic filling in coal mines differs in many respects from the technique employed in metal mines; it is characterized by rather shallow depths, large range of particle size, intermittent filling with small quantities, and relatively low pulp densities. Glacial material, silt, or culm, the finely divided waste product from coal preparation plants, is commonly used for fill material, although many other materials are satisfactory.

After visiting the Pennsylvania anthracite region in 1893, a party of German engineers introduced hydraulic filling in Europe where it rapidly became important. The Myslowitz colliery first used hydraulic filling extensively, and many other mines in Silesia soon followed. It was called "sand replacement" and was employed as an integral part of the coal-getting operation. This was in contrast to the applications in Pennsylvania where hydraulic filling had been principally used as a secondary, temporary, or stop-gap measure and was seldom employed for immediate support during extraction of coal from the face.

Hydraulic filling soon became standard practice not only in Silesia, but in Westphalia, France, and to some extent in Bulgaria, Servia, Poland, Spain, Austria, Hungary, Belgium, Italy, Britain, Russia, and Manchuria. The European technical literature of the period 1900 to 1915 contains many descriptions and discussions of these early operations.

Although a wide variety of materials was used for hydraulic filling in the European mines, glacial or fluvial sand and gravel, or crushed rock were chiefly employed. Because these unsized aggregates usually contain very little slimes and require large volumes of water, high velocities in the pipeline were so common that wear on the pipe became a principal source of trouble. Various kinds of pipe, including wood, terracotta, cast iron, wrought iron, mild steel, glass-lined, porcelain-lined, wood-lined, and pipe of oval shape with renewable iron liners were investigated and compared. The most difficult problems confronting the engineer were wear on the pipe, lack of sufficient fill material, and the difficulty of clarifying and lifting the stowing water.[3]

Hydraulic filling is still used extensively in Silesia [4] where sufficient surface material is available, but in other parts of Europe it has been curtailed or abandoned in favor of pneumatic and mechanical methods.

In recent years hydraulic filling has been widely practiced in the Jharia and Raninganj coal fields in India.[5] The government and the coal mining industry have cooperated in developing economical methods of using river sands for filling. The program is aimed primarily at the conservation of coal reserves by leaving a mined area in good enough condition that it can be mined at a later date either for recovery of the pillars or for overlying narrower seams.

Although hydraulic filling was used at an early date in the lead mines of Germany, the gold mines of Australia, and at Cripple Creek, Colorado [6]—operations that have not been well documented—it was first applied in large-scale metal mining on the Witwatersrand in South Africa. The Village Main gold mine began placing stamp sands underground hydraulically in 1909. Other hydraulic filling operations were soon begun at the Ferreira, Geldenhuis Deep, Robinson, Simmer and Jack, and Cinderella Deep, and have since been employed at most of the mines on the Rand for such varied purposes as support for current stoping, reclaiming pillars, mining parallel reefs, protecting drives, and controlling rock bursts.

Millions of tons of tailing have been placed underground at the South African mines; several mines have placed much more than a million tons each. The material used for filling at first was exclusively stamp sands, and was of such size that most of it would be retained on a

[2] Ash, S. H., and Westfield, James, Backfilling problems in the anthracite region as it relates to conservation of anthracite and prevention of subsidence: U. S. Bur. Mines, Info. Cir. 7843, 18 pp., 1946.

[3] Paton, J. Drummond, Modern developments in hydraulic stowing, and suggestions for its application in British collieries: Inst. Min. Eng. Trans., vol. 47, 31 pp. 1913-1914.

[4] Whetton, J. T., Gob stowage: Colliery Eng., vol. 25, no. 292, p. 188, no. 293, p. 235, and no. 294, p. 255, 1948.

[5] Turton, A. C., Sandfilling at Mufulira: Inst. Min. Met. Bull. 478, 24 pp., 1946; Discussion and reply Bull. 480, pp. 1-10, 1946.

[6] Origin of sand filling: Min. Sci. Press, vol. 109, p. 791, 1914.

100-mesh screen. Modifications in the milling practice have lowered the average grain size of the sands, but the South African sands are still coarser than most of the tailings available from modern flotation mills. Hydraulic-filling practice on the Witwatersrand, where the dip of the ore bodies is rarely greater than 35 degrees, is characterized by this particle size and by the use of sand cones, boreholes, underground distribution launders, and filter-bulkheads. However, as in all hydraulic filling applications, the details of practice vary greatly from mine to mine.

Hydraulic filling was used at Butte prior to 1920 for combating mine fires. Except for the small hydraulic-filling operation at Cripple Creek, this application appears to be the first use of hydraulic filling in the metal mines of the United States. The use of hydraulic filling for fighting mine fires has become an accepted effective technique. It has been successfully employed against fires at the United Verde, the Tintic Standard, and at other metal mines and coal mines throughout the world.

At the Matahambre copper mine, Cuba, in 1927, hydraulic filling was adapted to the cut-and-fill method of mining a steeply dipping vein. The fill material, mill tailing, was reduced to a very low slime content before being sent underground. The installation of rubber-lined pipe was found to be necessary, as it has in many hydraulic-filling systems since then. Regardless of the cost of the rubber-lined pipe, however, hydraulic filling reduced the total cost of mining and was beneficial in several other respects.

There soon followed several more applications of hydraulic filling in metal mines throughout the world; these applications at more mines and to different filling problems continue to grow in number. About the time that large hydraulic-filling operations were begun in the copper mines at Mount Lyell, Tasmania, and at Mufulira, Northern Rhodesia, 1929-32, the Homestake mine applied hydraulic filling to the control of surface subsidence. Using tailing from the cyanide sand-leaching operation, hydraulic filling soon became a part of the regular mining method. The Homestake Mining Company has developed the techniques of hydraulic filling to a high degree; the Company can completely recover an irregular ore body by a selective method of mining at a minimum cost.

In 1940 hydraulic filling was introduced at the Sliger mine, Georgetown, California. Large savings in labor and timber were realized.

Since World War II hydraulic filling has been introduced in many mines, including the South mine, Frood-Stobie, Holden, Greater Butte Project, New Brunswick, Central Eureka, and Dayrock. The last three mines are all cut-and-fill operations; small fills are deposited. The practice of hydraulic filling as employed at these mines appears to have evolved into a rather distinct system, which is proving very effective.

PROPERTIES OF HYDRAULIC FILLS

Cementation. Although little cementation of hydraulic fills is observed, even after several years, the lack of cementation does not significantly impair the effectiveness of the fill. Experiments on fill material at the Sullivan mine have shown that the time required for cementation is considerably longer for fine material than for coarse sands or waste. Thus mill tailings—especially those with a high proportion of slimes—may be expected to require many years for complete cementation. Most fills apparently are compressed to the maximum before sufficient time has elapsed for much cementing to take place.

Because the chemical composition and environment of any fill determines the effectiveness of cementation, the results obtained are seldom identical. Although the fills at both Butte and Mufulira are in sulfide areas, the percolating sulfate waters have caused no extensive cementing during the period of observation, which has exceeded ten years at both mines.

Few fills consisting of tailing contain much sulfide. In South Africa some of the fills have a pyrite content as great as 4 percent, but even these show no cementation. The tailing used at Homestake, which contains as much as 2 percent sulfides, usually cements to a shallow depth around the edges of the fill. The cemented material resembles a moderately indurated, ferruginous sandstone. Larger amounts of sulfides have been introduced into granulated slag and into sink-float tails in order to produce a thoroughly cemented rocklike fill. These cement well in a relatively short time, but develop high temperatures during oxidation.

Calcareous material may also produce a cemented fill. Only 7 months after deposition, the 55-percent limestone fill at Cerro de Pasco required blasting to drive through it. The 85-percent dolomite material used in a southeast Missouri hydraulic grouting operation cemented sufficiently to recover drill cores 6 inches in length.

The methods of chemical soil solidification that have been developed recently may eventually prove to be a valuable adjunct to hydraulic filling, especially as an emergency measure.[7]

Consolidation. Consolidation is used to mean the compaction or "setting up" of the material within a fill, exclusive of cementation. It depends chiefly upon the retained moisture and the slime content. The amount of moisture retained in a fully drained fill may be as much as 15 percent of the weight of the fill. Moisture content of the Mufulira fill, for example, was 11 percent 2 years after deposition. Except for coarse sands, the material of most fills is damp to the touch even after many years.

The slime assists the consolidation of the fill in two ways: it is important in retaining water, and it provides closer packing of the particles, the finer ones filling interstices. If the amount of slimes is too great, however, too much water may be retained and poor consolidation will result.

Examination of fills several months or more after deposition shows that the degree of consolidation varies considerably from mine to mine. Some fills react as crumbly aggregates and can be easily broken up; others are more blocky, as the material will hold together in chunks. Most fills, however, especially if there is sufficient slime, are firmly compacted, and will retain a sharp imprint of any tool thrust into them. A shovel, for example, can be easily driven into the material, but this does not

[7] Johnson, J. W., and Riedel, C. M., Water stopped in Alpha Slope by chemical sand solidification: Coal Age, vol. 54, no. 7, pp. 78-79, July, 1949.

Jorgensen, Lars R., Solidifying gravel, sand, and weak rock: Western Construction News, no. 10, 1931.

Polivka, M., Soil solidification by means of chemical injection: Univ. California, unpublished thesis, 1948.

cause the material to loosen or run. Most hydraulic fills will stand up well in free vertical faces. None is known to behave as a clean dry sand with uninhibited running tendencies, although the coarser the material, the more a fill might be expected to approach such a condition. The fills in South Africa are an example.

The effectiveness of a hydraulic fill for support is evidently unchanged by the manner of consolidation.

Routine mining methods are employed at many mines in which free vertical faces of hydraulic fill are exposed. In cut-and-fill mining, heights of two floors are commonly exposed, and greater heights are known. The South African practice of mining parallel reefs by using the hydraulic fill of the underlying stope for the footwall of the overlying stope also demonstrates the satisfactory consolidation of hydraulic fills.

Whenever the free side of a high fill is to be later exposed, safe practice requires that a bulkhead be constructed so that the material will be contained at the time of exposure. Maximum height to which the material will stand sufficiently well without a bulkhead depends upon the manner in which the fill consolidates, and must be determined by experience; both the Homestake mine and the South Mines have constructed bulkheads.

Compressibility. Many observers agree that hydraulically deposited sands or other fine material are the least compressible materials used for mine filling.[8] Rarely does hydraulic fill compress more than 20 percent; measurements and estimates generally indicate from 5 to 10 percent.[9] Hydraulic fills are more resistant than other fills because water-deposited particles are very compact and because the innumerable small particles provide a large bearing surface.

The strength of a hydraulic fill is not developed until sufficient dewatering has changed the material from the quick condition to the consolidated condition. Pressure on a poorly consolidated fill causes flowage and is sometimes transmitted through the fill, as though it were a fluid, to the bulkheads.

Permeability. The permeability of a fill is important. It is more important in large fills than in small ones. Large fills must be either impermeable, a rare condition, or they must be sufficiently permeable to permit the quick dissipation of any amount of water that may find its way into the fill so that the water will not form ponds or otherwise be retained. Enough water in the fill either from poor original dewatering or from subsequent influx, to cause a mushy or quick condition may cause immense pressures on the bulkheads which may not become evident before the bulkheads burst. Suitable permeability will permit any water that might enter to drain off through fissures in the adjoining rock or through the drains provided in the bulkheads.

[8] Griffith, Wm., and Conner, E. T., Mining conditions under the city of Scranton, Pennsylvania: U. S. Bur. Mines Bull. 25, 1912.
Jeppe, C. B., Gold mining on the Witwatersrand: Transvaal Chamber of Mines, vol. 1, pp. 814-826, 1946.
Watermayer, G. A., and Hoffenberg, S. N., Witwatersrand mining practice: Gold Producers' Committee, Transvaal Chamber Mines, Johannesburg, South Africa, pp. 459-471, 1932.

[9] Jones, A. A., Sand filling methods at Hodbarrow mines, South Cumberland: Inst. Min. Met. Bull. 229, pp. 1-19, 1932; Discussion: Bull. 330, pp. 1-13; Reply: Bull. 332, pp. 51-53.
Eaton, Lucien, Sand filling through pipes and boreholes: Am. Inst. Min. Met. Eng. Trans., vol. 102, pp. 33-41, 1932.
Richert, George L., Mining methods at Mines De Matahambre, Matahambre, Pinar Del Rio, Cuba: U. S. Bur. Mines Info. Circ. 6145, pp. 8-9, 1929.

The permeability of small fills is probably less important because entrapped water may drain through less fill material, as the proportion of wall rock surface and bulkhead surface exposed to the fill is much larger. Also, the condition of the bulkheads is more easily observed and dangerous conditions can be detected.

In addition to required minimum permeability of the emplaced fill, the permeability of the fill at the time of deposition is important in determining the methods of dewatering to be used.

The permeability of a fill, and consequently the rate of percolation, depend chiefly on the slime content of the fill material, although the effect of other factors, such as the range of sizes and shape of particles, are important.

Slime Content. Control of the amount of slimes in the fill material is very important. The slime content is a factor in the cementation and consolidation of fills, and is important for its effect on viscosity and abrasion during the transportation of the pulp. However, the amount of slimes is probably most important in its effect on the permeability of the fill and the methods used for dewatering. There is a maximum limit to the amount of slimes that is satisfactory.

The effect of slimes is easily demonstrated in the correlation between the types of bulkheads and the slime content of the fill material with which they are used. Filter-bulkheads are ordinarily used with fills that are comparatively coarse and contain few slimes. Most of the dewatering is accomplished by percolation with final egress of the water through the bulkheads. The fills at Hodbarrow, the Emma and Travonna mines in Butte, the Matahambre mine, and on the Witwatersrand[10] are examples (see table 2).

Fills consisting of finer material require at least partial dewatering by decantation or by continual draining of water from the surface of the fill. The fills at Central Eureka, Dayrock, Great Boulder, New Brunswick, Sliger, and the South Mine are examples. After these fills have become consolidated only part of any water that is run in on top of the fill will seep slowly into the fill; most of it will flow over the surface and seek an outlet elsewhere.

The effect of slimes on permeability and percolation rate has been studied at a few of the mines. The work is difficult to correlate because the tests are conducted for different purposes, the methods employed in testing are not the same, and the results are recorded in different units. The distinction, for example, between fines, slimes, and true colloidal phases is not always clear. Probably there is a lower limit of particle size below which the suitability of any material rapidly diminishes, especially if such sizes are present in large quantities. This limit is undoubtedly not the same with different materials and therefore no generally applicable figure is to be expected.

An arbitrary limit on the amount of slimes allowable in fill material is set at some mines. At the Sullivan mines, for example, where glacial drift is used, 15 percent is the maximum amount of minus 200-mesh material permitted. Large stopes are filled hydraulically, but the methods of hydraulic filling as defined herein are not used.

[10] Regardless of the apparently satisfactory permeability of the coarse sands commonly used on the Rand—drainage is almost always provided for by percolation methods—occasionally destructive washouts have occurred due to the accumulation of water within the fill.

At Homestake, percolation tests on fill material obtained from the sand-leaching plant and deslimed at a separation near 325 mesh, have shown that an increase of several percent in the minus 200-mesh portion, which ordinarily runs about 45 percent, reduced the percolation rate only slightly. However, it was also shown that an increase in the minus 325-mesh portion of only 1 percent reduced the percolation rate by 50 percent. The material is derived from a schistosic ore.

At Mulfulira[11] a change in mill practice increased the pulp density of the feed to the desliming cones, consequently, the amount of minus 325-mesh material going underground increased from 13 to 22 percent. The cumulative minus 200-mesh material increased only 1 percent. As a result of the increased slimes a major bulkhead failed causing a bad spill, and a thin pillar of rock (the "mud-seam") between the parallel stopes also failed. This was corrected by diluting the feed to the cones until the quantity of minus 325-mesh in the fill material was reduced to its original value. Fifty percent of the minus 325-mesh is said to be colloidal. The cumulative, minus 200-mesh fraction equals 32 percent.

Prior to the introduction of hydraulic filling at the Great Boulder mine [12] several test runs were made in a stope on the 300-level. The stope was 100 feet long, 4 feet wide, and was sealed with water-tight bulkheads at the ends. Before the first fill was deposited, used filter cloths were placed on top of the waste fill already in the stope. Thereafter, drainage was chiefly through a perforated vertical pipe in which the holes were plugged as the level of the fill rose, thus decanting the excess water. Four runs of fill, in amounts up to 85 tons, are recorded in table 1. These fills required from 3 to 14 days to dry at the surface and remained puggy several more days. They required up to 6 weeks to dry. Thereafter, the material used in fills was classified before being sent underground and the amount of slimes greatly reduced (table 1). According to the report, "the resultant surfaces were all excellent and the drying time was less than 24 hours." Since these experiments were performed, the results of actual operations have shown that the slime content can be increased to 50 percent and still be within satisfactory limits.

The results so far obtained indicate that the effect of slimes in hydraulic filling is great. Precisely what effect slimes will have in any mine cannot as yet be predicted with accuracy; it is known, however, that too high a percentage of slimes may be damaging.

APPLICATIONS OF HYDRAULIC FILLING

Hydraulic filling can be used in any application for which conventional fills are used and is especially suited to certain uses. In most operations it serves more than one function.

Control of Subsidence. The effectiveness of hydraulic fills for support of the overlying strata is due to the strength and low compressibility of such fills. Hydraulic

[11] Turton, A. C., Sandfilling at Mulfulira: Inst. Min. Met. Bull. 378, 24 pp., 1946: Discussion and reply Bull. 480, pp. 1-10, 1946.

[12] Holly, J., Yates, C., Finucane, K. J., and Gillie, E. W., Stope filling with thickened classified flotation tailings: Australasian Inst. Min. Met. Proc., vol. 137, pp. 1-11, 1945.

[13] Holly, J., Yates, C., Finucane, K. J., and Gillie, E. W., Stope filling with thickened classified flotation tailings: Australasian Inst. Min. Met. Proc., vol. 137, pp 1-11,1945.

Table 1. Pulp densities and screen size of material used in experimental hydraulic filling at the Great Boulder mine[13]

Test	Pulp density percent solids	65-mesh percent	−65+200-mesh percent	−200-mesh percent
		A		
1	65	2.5	24.1	73.4
2	65	2.2	23.0	74.8
3	66	0.3	21.3	78.4
4	63	1.4	22.8	75.8
		B		
1	65	----	----	36.8
2	68	----	----	27.1
3	67	----	----	35.0

fills have been employed in order to minimize surface damage,[14] to facilitate the mining of parallel hanging-wall stringers,[15] to permit mining below water-bearing formations [16] and to protect underground workings.[17]

Table 2. Average screen analyses of material used for hydraulic fills at various mines

Locality	−65-mesh percent	−200-mesh percent	Remarks
Butte, Emma and Travonna	----	----	Decomposed surface rock.
Butte, (fire fighting)	----	52	
Butte, (greater Butte project)	nil	30	
Central Eureka	1	45	
Cerro de Pasco	----	55	
Dayrock	4	35	
Frood-Stobie	10	20	
Great Boulder	2	48	
Hodbarrow	----	----	Dune sand, analysis unknown.
Holden	----	35	24% in plus 100-mesh.
Homestake	3	44	From sand-leaching plant. Very little minus 325-mesh.
Matahambre	49	3	Note lack of slimes.
Mount Lyell	7	39	17% is minus 325-mesh.
Mufulira	6	24	13% is minus 325-mesh of which about 50% is colloidal.
New Brunswick	18	30	
Sliger	nil	25	
South Mine	17	30	Approximate conversion from IMM screen series.
Witwatersrand (South Africa)	----	----	Formerly mostly plus 100-mesh. Now may be somewhat finer.

Stope Support During Mining. Hydraulic filling has always proved advantageous where it is used as an integral part of the stoping operation. The quick, effective support of the walls reduces sloughing and slabbing from the back, allows safer mining, and helps substantially toward minimizing dilution. Commonly it has been

[14] Ross, A. J. M., Sand filling at the Homestake mine: Min. Tech., vol. 3, no. 4, 15 pp., 1939. Am. Inst. Min. Met. Eng., Tech. Paper 1075.

[15] Watermeyer, G. A., and Hoffenberg, S. N., Witwatersrand mining practice: Gold Producers' Committee, Transvaal Chamber Mines, Johannesburg, South Africa, pp. 459-471, 1932.

[16] Jones, A. A., Sand filling methods at Hodbarrow mines, South Cumberland: Inst. Min. Met. Bull. 329, pp. 1-19, 1932; Discussion: Bull. 330, pp. 1-13; Reply: Bull. 332, pp. 51-53.
Turton, A. C., Sandfilling at Mufulira: Inst. Min. Met. Bull. 478, 24 pp., 1946; Discussion and reply Bull. 480, pp. 1-10, 1946.

[17] Watermeyer, G. A., and Hoffenberg, S. N., op. cit., 1932.
Jeppe, C. B., Gold mining on the Witwatersrand: Transvaal Chamber of Mines, vol. 1, pp. 814-826, 1946.

possible to modify the method of mining to permit savings in labor, timber, and development work. Hydraulic filling permits maximum selectivity, flexibility, and rapidity in stoping operations. The fills ordinarily consolidate sufficiently to permit resumption of mining within 24 hours.

Some of the achievements in stoping credited to hydraulic filling are remarkable. The Central Eureka and New Brunswick mines, for example, were able to convert square-set stopes to cut-and-fill methods. At the Sliger mine the layer of serpentine gouge 100 feet thick along the hanging wall was so effectively held as to reduce the timber required by more than 50 percent. At the Dayrock and Matahambre mines modified stope layout decreased the amount of development work. The necessity of leaving crown pillars at the Homestake mine was entirely eliminated.

Pillar Recovery. On the Witwatersrand the value of hydraulic filling for the recovery of pillars is undisputed, except in the deep mines. As in most other applications of hydraulic fills, it is the strong compressive strength and rapid succession of mining, filling, and taking weight that makes hydraulic filling suitable for use in pillar recovery. When the concentration of stresses in pillars is lessened by quick and effective support within the adjacent excavations the mining of the pillars proceeds rapidly, reducing cost and increasing safety and the maintenance of access through pillars is facilitated.[18]

Mine Stabilization. Hydraulic filling has been effective in improving the general stability of ground in mines. In mines containing large open stopes it has helped to minimize ground movement and diminish the possibility of rock-bursts. Hydraulic filling is being used to stabilize previously mined ground in preparation for large-scale block caving at Butte.

Control and Prevention of Mine Fires. Hydraulic filling has controlled many sulfide and timber fires in metal mines, even after other methods have failed. According to Rahilly,[19] it is particularly effective with inaccessible fires of large extent and high temperature. Usually hydraulic filling is employed for fire fighting by inundating with fill material the entire area in which the fire is burning.[20]

Drainage Control. In the southeast Missouri lead district hydraulic filling has been employed to control the flow of underground water that was entering the mines through solution channels in dolomite. The water was effectively dammed by the introduction of mill tailing through boreholes into areas adjoining the mines.[21]

Tailing Disposal. Although hydraulic filling has never been used in metal mining exclusively for the purpose of disposing of the tailing, such disposal might be economical where land is valuable, streams are seriously polluted, or it is expensive to prepare for tailing storage.

Effects on Mine Ventilation. Ventilation of mines is commonly improved when hydraulic filling is substituted for filling with waste. The air does not short-circuit through the fill and the maintenance of openings required for ventilation is facilitated.

Where the fill material is tailing from a cyanide plant, precautions may be necessary to prevent the generation of hydrogen cyanide. The Mine Regulations in South Africa impose a limit of 0.005 percent potassium cyanide in the moisture of the fill and in the water that drains from the fill. In order to keep within this limit an oxidizing reagent is added to the alkalized pulp that goes underground to oxidize the cyanide to the innocuous cyanate.[22]

At the Homestake mine the material from the sand-leaching plant requires no special treatment. The water draining from the fill is neither harmful to the skin nor dangerous if taken internally. The material used at Holden, which also contains some cyanide plant tailing, also requires no special treatment and produces no harmful effects.

Hydraulic filling increases the humidity of a mine and therefore may add to the ventilation problem. Also, openings into a hydraulic fill are sometimes deficient in oxygen and need special ventilation. The heat of oxidation from a hydraulic fill probably never is great enough to be troublesome, since the oxidation proceeds too slowly.

Techniques

Preparation of the Pulp

Before the fill material is sent underground it must first be mixed with water at the preparation plant, which also controls somewhat the quality of the pulp.

The chief functions of a preparation plant are regulation of the volume or velocity, control of the pulp density, provision of homogeneity in the pulp, and regulation of the slime content. Precise control of these factors is seldom required and therefore elaborate equipment is rarely warranted.

Some preparation plants provide a continuous flow of pulp, whereas others prepare the pulp in batches for intermittent delivery. A continuous type plant is limited in the rate of output to the rate of feed, and fluctuations in the feed or discharge usually affect the efficiency of the unit. Where the pulp is sent underground in a closed pipe,[23] gravity system, the rate of discharge will vary with the depth and horizontal distance to which the material is being conveyed. Because of these limitations a continuous-discharge system is practically restricted to use

[18] Ross, A. J. M., Sand filling at the Homestake mine: Min. Tech., vol. 3, no. 4, 15 pp., 1939. Am. Inst. Min. Met. Eng., Tech. Paper 1075.
Plumb, C. W., Filling mine stopes with mill tailings: Min. Cong. Jour. vol. 28, no. 1, pp. 12-14, 1942.
Assoc. Mine Managers Transvaal, Some aspects of deep level mining on the Witwatersrand gold mines with special reference to rock bursts: Transvaal Chamber Mines, Johannesburg, South Africa, 1933.

[19] Rahilly, H. J., Mine fires and hydraulic filling: Am. Inst. Min. Met. Eng. Trans., vol. 68, 12 pp., 1923.

[20] Alenius, E. M. J., Methods and costs of stripping and mining at the United Verde open-pit mine, Jerome, Arizona: U. S. Bur. Mines Info. Circ. 6248. p. 34, 1930.
Brusset, J., Battling a mine fire in Algeria: Explosives Eng., vol. 8, no. 3, 4 pp., 1930.
Hanson, Earl F., Control of underground mine fires at Tintic Standard mine: Am. Inst. Min. Met. Eng. Trans., 126, 12 pp., 1937.
McCutchen, V. L., Mining methods at the Cerro de Pasco properties: Mining and Metallurgy, vol. 26, no. 467, pp. 521-523, 1945.
Rahilly, H. J., op. cit., 1923.

[21] Weigel, W. W., Mine drainage, southeast Missouri lead district: Am. Inst. Min. Met. Eng., Trans., vol. 153, 8 pp., 1943.

[22] Jeppe, C. B., Gold mining on the Witwatersrand: Transvaal Chamber of Mines, vol. 1, pp. 814-826. 1946.

[23] Closed pipe is used to indicate a continuous, unbroken line, from the tank of the preparation plant to the point of discharge in the stope. The term open pipe means that somewhere the line is open to the air.

with large fills where conditions are constant for considerable periods of time and where the pulp is either pumped from the plant or transported in an open pipe, gravity system.

Simple Sluicing Plants. The simplest type of plant provided only for sluicing the material from dumps, storage bins, or leaching tanks into pipelines, boreholes, or launders. This system obviously has merit for simplicity and economy of investment. It has been particularly successful in shallow mines where the pulp could be introduced directly into the stope through a borehole. It is not useful in small, widely scattered fills because it cannot be controlled through long pipelines. Unnecessarily large amounts of water are often introduced into the mine.

Sluicing systems were extensively used in South Africa where rather low pulp densities were used in the underground launder system. Other sluicing systems were used at Hodbarrow and at the United Verde sliming operation.

Thickeners, Classifiers, and Sand Cones. These devices are employed for better control of the pulp than is possible in sluicing plants. They are well adapted to handling large tonnages and are easily arranged to permit continuous operation.

Sand cones have been used extensively on the Rand, at the Mufulira mine, and at Homestake during the early years of hydraulic-filling. They are erected directly over boreholes.

At Mufulira, sand cones were used after it was found that they recovered more of the fines than a classifier and yet made a suitable separation of the true slimes. Batteries of four locally constructed wooden cones are used. They give a recovery of 58 percent of the solids at a feed density of less than 30 percent solids, and have a capacity of 1,400 to 1,500 tons per day per battery.

Sand cones on the Rand are used chiefly for dewatering the sand after pumping it a long distance at low density. At the Government Gold Mining Areas, for example, batteries of 16 cones are used at each borehole. They are capable of handling 2000 tons of sand in 8 hours with discharge at 70 percent solids. The sand cones at Homestake were likewise used principally for dewatering after pumping.

FIGURE 1. Thickener-type preparation plant.

Classifiers were used at the Matahambre mine to reduce the minus 200-mesh fraction in the mill tailing from 49 percent to only 3 percent.

At the Holden mine a thickener is used for pulp density control and for mingling the two different tailing products that are used as sources for the fill material. The discharge from the thickener, about 50 percent solids, is fed to pumps and must be uniform (fig. 1).

Agitators. The third and largest group of preparation plants is that in which agitators are employed. The agitator is a means of smoothing out surges in the feed to the pipeline, and is employed primarily as a device to provide a supply of homogeneous pulp. It is most satisfactory where large volumes are handled and desliming is not important. Equipment ranges from small tanks with compressed air agitation to large installations with agitation by a combination of methods. Where the control of density or slimes is important, thickeners or classifiers are sometimes used in conjunction with agitators. In general, an agitator plant requires close surveillance during operation.

At the Great Boulder mine and at Mount Lyell the agitators are preceded by combination thickener-deslimers. This arrangement permits continuous desliming of the mill discharge with intermittent discharge of the pulp to the stopes, and provides excellent control of slimes and pulp density. The control of pulp density is especially necessary at Mount Lyell where all the fill material is pumped upward into the mine and the point of discharge varies widely in elevation and distance from the preparation plant.

The Homestake agitator plant consists of a 12-foot diameter Dorr dewaterer with four rakes revolving at 5 revolutions per minute. The sand from the leaching tanks is sluiced either directly into this agitator or into a settling pond behind a small dam for temporary storage. The sand in the pond is then sluiced to the agitator whenever it is needed underground. The pulp density is regulated by adding water or by dewatering at the agitator, although often no regulation is necessary. Seven hundred tons of sand from one leaching tank is handled per shift. If such a plant could be laid out more compactly only one operator would be required.

At Butte the mill tailing is sluiced by high-pressure jets directly from railroad cars into a 25-foot diameter agitator beneath the tracks. Agitation is provided by an impeller turning at 25 revolutions per minute and driven by a 50-horsepower motor. A similar plant of large capacity is used at the Frood-Stobie mine, but here the dry tailing is dumped first into a storage bin and then sluiced into a 12-foot agitator equipped with a rake mechanism.

Another arrangement was used at the Sliger mine. Tailing from the mill, in the form of dilute pulp, was collected in a storage tank and allowed to settle; some desliming was thus effected. It was then sluiced by various means from this tank through a small agitator into the underground pipeline. This system did not provide easy control of the pulp density and required constant attention during operation.

Several features of the Sliger operation should be noted: storage of the mill tailing was necessary in order to convert the continuous discharge of the mill to an intermittent discharge for filling; some desliming was desirable; some thickening was necessary; a homogeneous pulp was desirable because it would eliminate much of the pipeline trouble; the volume of material to be handled was comparatively small. This is a combination of circumstances that may be expected to exist at many mines of moderate size. It was to satisfy conditions such as these that the following type of plant was developed.

Strict Batch Agitation. This kind of plant is now used at the New Brunswick, the Central Eureka, and the Dayrock mines.[24]

One unit of equipment is employed, a combination deslimer, thickener, and agitator. Details of design and operation can be varied to effect almost any desired control over the pulp. Tailing is run into the tank from the mill until the depth of settled pulp indicates that a sufficient quantity is available to provide the desired pulp density when the water level is at a certain height. Desliming is controlled by the length of overflow weir and by the arrangements for introducing the tailing into the tank. After the tank is charged with tailing and water in correct ratio, feed from the mill is by-passed to the tailing pond or to another similar tank. The tank of tailing is then mixed by a mechanical impeller assisted by air jets located directly below the impeller and around the periphery of the tank. Only after the pulp has become thoroughly homogeneous is it turned into the pipeline leading to the mine. One man is required for operation of the tank.

This kind of plant has been used exclusively with closed-pipe systems. Owing to the complete control of pulp density and the reliable operation resulting therefrom, this strict batch agitation type of plant has been quite successful. It is particularly good where small fills are placed (see figs. 2 and 3).

Figure 2. Batch-agitation plant. This is the New Brunswick mines tank which has a capacity of 240 tons per batch.

Figure 3. Central Eureka double-tank batch agitation plant.

Underground Plants. Dry material is mixed into a pulp underground in two localities. This method requires provision for getting the dry material underground, may necessitate excavation for the mixing apparatus, and limits the radius in which gravity hydraulic-filling operations are possible.

At the Emma and Travonna mines in Butte the decomposed granitic material is dumped down waste-passes and drawn off one level above that on which it is to be used. Air-powered, screw-feeders carry the sand into launders from which it is sluiced into the pipeline and conveyed to the level below. In certain square-set stopes where only small volumes of fill are required at a time, the dry sand is dumped down the service raises and drawn off in the stopes by bazookas, which are simple water-jet devices that mix the sand in the chute with enough water to cause it to flow freely in a launder to all parts of the stope.

Several underground mixing stations are used at the South Mine, Broken Hill, and are located throughout the mine to provide hydraulic filling to stopes in all areas of the mine below the stations. The apparatus consists essentially of conical-shaped, wooden receivers, equipped with suitable screens and water jets that draw the dry tailing from the sand passes and mix it with appropriate amounts of water for it to flow through the pipelines. One man can operate two stations. The mixing is done underground chiefly because of the storage capacity provided in the sand-passes; large volumes of fill material are required at irregular intervals inconsistent with the output of the mill.

Construction of Slime Ponds. The ponding of slimes may be required at a mine where the mill tailing must be deslimed before being sent underground. It was reported from the Sliger operation "that by careful work, a very excellent pond can be made from the slimes themselves."[25] Experience at the Central Eureka has also shown that a good pond can be constructed. The discharge of slimes into the pond is shifted regularly to permit localized drying so that the slimes can be shoveled into dykes where they make a tough, leathery bank.

[24] Krebs, Richard, and O'Donnell, J. C., Sand-slime stope filling proves satisfactory: Eng. and Min. Jour., vol. 150, no. 1, pp. 54-60, 1949.
Sand filling pays off: Mining World, vol. 11, no. 11, pp. 34-36, 1949.

[25] Plumb, C. W., Filling mine stopes with mill tailings: Min. Cong. Jour. vol. 28, no. 1. pp. 12-14, 1942.

Table 3. Details of some closed-pipe, gravity transportation systems

Location	Kind of pipe	Pipe size (in inches)	Maximum elevation of head (in feet)	Horizontal to vertical ratio (average)	Velocity (feet per second)	Percent solids	Dry tons per hour average	Screen analyses (percent)		Tonnage passed	Resultant wear
								+65	−200		
Central Eureka	steel	2	3600 [a]	1.2:1	7.5	68-70	30	1	45	27,000	insignificant
Dayrock	steel	3	228 [b]	3.5:1	[n]	66-76	60	4	35	little to date	--
New Brunswick	steel	2	1600	3.7:1.	9-12	72-74	35	30	30	100,000	slight
Sliger	rubber hose [c]	2	1450	[n]	[n]	65-70	50	nil	25	100,000	negligible

[a] 3000 feet uninterrupted in 70° inclined shaft—total length of line 8,200 feet.
[b] To be extended considerably.
[c] Special construction—installed after steel pipe wore rapidly.
[n] No data available.

Transportation of the Pulp

The transportation of the pulp from the preparation plant to the workings may be accomplished by several methods. These include gravity systems, employing pipelines, launders, or boreholes, and pumping systems, or a combination of methods. The most suitable system is determined largely by the layout of the mine and plant, the tonnage requirements, and the physical character of the pulp, especially the settling rate and the abrasiveness.

In all systems the pulp density should be as high as possible to minimize the amount of water introduced into the mine; it is usually limited to the density at which plugs or spills occur. The velocity should be as low as possible in order to minimize wear and yet handle the required tonnage.

Closed Pipe, Gravity Systems. A common means of conveying the pulp underground is through a closed pipe in which there is no break nor opportunity for air to enter; the pulp flows at constant velocity throughout the length of the line if the pipe size remains the same. This system has been used chiefly in connection with the strict batch-agitation surface plants, for which it is ideally suited. Closed-pipe systems may not be well suited to applications in which tonnage requirements necessitate large size lines, but where it is applicable, it provides good control over the velocity and thereby may sometimes allow substitution of steel for rubber-lined pipe. Surging and heavy vibration do not occur in a closed-pipe system. Details of four of these systems are given in table 3.

Once a line of this type has been installed, it is obvious that the interrelations of density, viscosity, and friction are important; they control the tonnage transported and the velocity. Variations in the location of the underground discharge necessitate some control of the system and this is usually obtained by regulation of the pulp density. The coincident effect on viscosity and friction is important. The viscosity increases with increased pulp density, and may vary proportionally over a considerable range.[26] The friction, therefore, also varies with the pulp density, but likewise is not always proportional.

At the New Brunswick mine, for example, increasing the density of the pulp being delivered to a given level decreases the velocity. Likewise, with a constant density, a lower elevation of discharge decreases the velocity, indicating that the friction head increases faster than the static head.

[26] Hudspeth, H. M., Pumping tailing for mine filling at Mount Lyell: Chem. Eng. and Min. Rev. vol. 31, pp. 414-417, 1939.

The effect of friction is conspicuously demonstrated at the Central Eureka mine where pulp of 70 percent solids flows at 7.5 feet per second although the elevation head is 3,600 feet and the ratio of horizontal to vertical pipeline length is only 1.2 to 1. Small variations in density do not cause much variation in velocity in this line due to the length.

The depth to which a closed-pipe system can be used is not known. Probably one could be carried considerably deeper than the present maximum of 3,600 feet. There is undoubtedly some depth below which extra heavy pipe or pressure-release valves would have to be installed. Although pressure in the line while the pulp is flowing is not great, a plug may cause high static heads. The longest steep section in the ordinary steel pipeline used at the Central Eureka is 3,000 feet down a 70-degree incline; this section has withheld the static pressures exerted when plugs occurred in the lower parts of line.

In determining the size of pipe for a closed pipe system the tonnage requirements are important, especially when steel pipe is used and the velocity must be kept at a minimum. From observation of the New Brunswick line it was concluded that a 3-inch line would have been better than the 2-inch line.[27] In order to get sufficient tonnage in the 2-inch line the density had to be lowered so as to gain higher velocity, which, in turn increased abrasion. If the density of a pulp remains the same, a small increase in the pipe size would provide a considerable increase in the tonnage without a large increase in velocity, because the only factor increasing velocity would be decreased friction, which varies as the square of the diameter. Any increase due to friction might be checked by further increasing the velocity. These relationships, however, cannot be expected to exist in very large or very small pipes. Another consideration in figuring the size of pipe is that the larger the pipe, the greater will be the total tonnage passed before replacement is required, because the higher viscosities allowed would result in less wear. The pipe size, however, cannot be so large that the density cannot be compensated for in large part by the friction head, because too great a velocity and a maximum suction head in the upper part of the system would be developed.

The 3-inch line at the Dayrock mine has not been extended far enough nor been used long enough to determine its characteristics and effectiveness.

[27] Krebs, Richard, and O'Donnell, J. C., Sand-slime stope filling proves satisfactory: Eng. and Min. Jour., vol. 150, no. 1, pp. 54-60, 1949.

Table 4. Details of some open-pipe gravity transportation systems ("mainline" or shaft piping only)

Location	Kind of pipe	Pipe size (in inches)	Maximum elevation head (in feet)	Horizontal to vertical ratio	Percent solids[a]	Dry tons per hour (average)	Screen analyses percent		Tonnage passed	Resultant wear
							+65	—200		
South Mine	steel	4	870	7.4:1[b]	70–75	160	17	30	500,000[b, c]	--
Frood-Stobie	rubber-lined	6	1200	[n]	60	125	10	20	[n]	[n]
Home-stake	rubber-lined	6	2300[d]	2.5[b]	65	100	3	44[e]	3,000,000	[f]
Meta-hambre	rubber-lined	2½	1700	3.0:1(g)	50	35	49	3	500,000	[h]
Gt. Butte Project	cast-iron[i]	6	3400[j]	2.7:1(k)	50–55	[n]	nil	30	little to date	--

[a] Measurements taken at agitator or mixer—density along lines varies owing to entrained air.
[b] Maximum tonnage to date.
[c] From four different "mixing stations"—no pipe replacement yet necessary.
[d] Maximum uninterrupted vertical drop of 1500 feet.
[e] Deslimed to almost no minus 325-mesh.
[f] In upper part of vertical sections.
[g] Average.
[h] No replacement necessary.
[i] Experimenting with rubber lining in upper 600 feet.
[j] 1000 foot maximum vertical interval between "break," and vent.
[k] Maximum allowable.
[n] Data not available.

Open-Pipe, Gravity Systems. An open-pipe system is so constructed that air is admitted to the pipeline, with the result that velocity probably varies along the length of the line, and in the upper parts of vertical sections the pulp probably drops freely. In some of the systems special provision is made to allow air to enter; in others the air is drawn in at the head of the line through the agitator of the slucing apparatus. This system has been used generally where greater tonnages are handled than by the closed-pipe systems, and where larger size pipes are used. Details of some of these systems are presented in table 4.

The exact conditions under which the pulp flows in open-pipe systems is not known. The intake end of the Homestake line, for example, draws in air and the discharge is violent with sprayed pulp and intermingled air under pressure. The velocity at the discharge appears to be considerably greater than the calculated velocity for pulp alone would indicate. This effect is noticeably different from those in the closed-pipe systems where the pulp issues in a smooth, quiet stream. At Butte the volume of air taken in through the air-intake valve at the collar of the shaft was found to be 6 times the volume of pulp. The diverse conditions within the line are further evident by the non-uniform wear along the line. The upper parts of vertical drops commonly show the greatest wear.[28] Irregularities in the alignment of the pipe in the sections where free falling takes place cause extreme wear. Vertical sections require strong support and careful blocking to check vibration.

The ratio of horizontal length to elevation head is important in all gravity systems. The conditions that exist below the area of "free fall" in the open-pipe systems are probably somewhat like those in the closed pipe systems, and are governed by the same relationships, i.e., density, viscosity, and friction. An outstanding example is reported from the South Mine, Broken Hill in which a pulp at 72 percent solids was run through a line in which the ratio of horizontal to vertical length was 7.4 to 1 (total length 1305 feet). The layout of lines for the Greater Butte project is based on the rule of allowing a ratio of 2.7 to 1. This contrasts remarkably with the former practice during the fire-fighting operations when pulp densities of 30 percent and a ratio of 8 to 1 were used. The lines at most mines are within a ratio of 3 horizontal to 1 vertical.

Open hoppers inserted in vertical lines at intervals of 300 feet have been used in South Africa and Europe in order to diminish "surging, hammering, velocity, wear, and pressure." They were originally used in Butte at intervals of 1000 feet. They are a disadvantage in that they limit the head that can be developed for propelling the pulp through subsequent horizontal lengths of pipe, and they are subject to spills. In favor of the use of hoppers, the breaks in the lines at Butte are now made by the introduction of two long-shanked tees with a short horizontal piece between them, thus keeping the line closed (fig. 4). From each break a 2-inch vent-pipe, equipped with a valve, extends upward about 40 feet. Whenever the pulp backs up to one of these vents the valve is closed, otherwise it remains open and either admits or ejects air, depending probably on the relative position of the bottom of the free fall area in the pipe.

Pumping Plants. The pumping of pulp for hydraulic filling is not unlike other pumping problems involving suspensions, except that high pulp densities are commonly employed. Table 5 gives details of some of the pumping plants that have been used in connection with hydraulic filling.

Except where raises are driven to provide all-gravity flow, some pumping, either of the mill tailing or of the prepared pulp, is required at most mines. Mount Lyell is apparently the only application to date of hydraulic filling at a mine in which all of the fills are deposited at an elevation above the level of the mill. Hydraulic filling here has proven successful, however, and costs are not excessive. Six pumps are spaced along a pipeline that delivers pulp to stopes that are as much as 10,700 feet in distance and 819 feet in elevation from the point of preparation of the pulp. All stations along the line are connected by telephone. Pumping is started with the fill material 50 percent solids and increased until any one pump is fully loaded. The pulp density varies considerably depending on the location of the stope and the amount of sealwater introduced by the pumps.[29]

[28] Watermeyer, G. A., and Hoffenberg, S. N., Witwatersrand mining practice: Gold Producers' Committee, Transvaal Chamber Mines, Johannesburg, South Africa, pp. 459-471, 1932.

[29] Horsefall, R. A., Flotation tailings for mine filling: Chem. Eng. and Min. Rev., Oct. 14, pp. 5-7, 1937.
Hudspeth, G. F., Pumping tailing for mine filling at Mount Lyell: Chem. Eng. and Min. Rev., vol. 31, pp. 414-417, 1939.

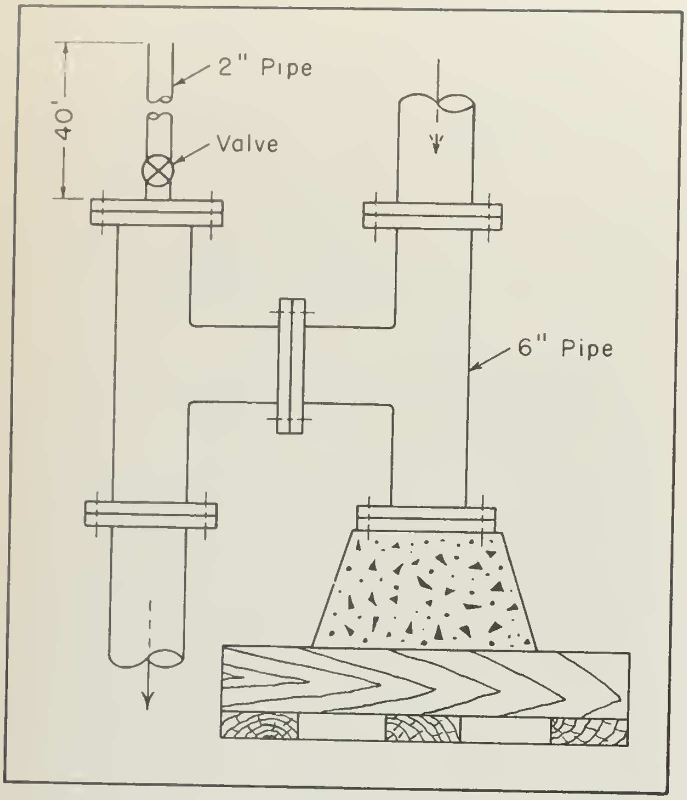

FIGURE 4. Velocity break for vertical sections in an open-pipe transportation system.

Pipe and Fittings. The kind of pipe used at any installation is governed chiefly by the cost, total tonnage to be passed, and the abrasive resistance that the pipe exhibits toward the particular pulp. High slime content, high pulp density, and low velocity tend to minimize abrasion.

Whether rubber-lined pipe should be used at a given mine is important because of the cost of the pipe. From the analyses presented in tables 3 and 4, it is evident that most of the installations of rubber-lined pipe have been in the open-pipe systems. In addition, rubber-lined pipe has been used at Mufulira where it was employed for distribution of the pulp from boreholes, and rubber hose was used at the Sliger mine. In all of the applications where rubber-lined pipe is used, except perhaps at the Frood, various other kinds of pipe, including all grades of iron and steel were first tried, but were found to wear rapidly.

In contrast to these results, the satisfactory application of steel pipe at certain mines is conspicuous, although it should be noted that at no plant using steel pipe has the total tonnage passed been great when compared to some of the others. Possibly for long life and great tonnage, a rubber-lined pipe should be installed in gravity operations regardless of whether an open-pipe or closed-pipe type of transportation system is used.

The choice of pipe to use in surface pumping plants, where the velocity is adequately controlled, or in underground distribution laterals, which will not carry so great a total tonnage, is not difficult. Table 5 indicates the kinds of pipe that are commonly used in pumping plants. Any kind of used pipe or other inexpensive, readily available pipe is generally used for underground laterals. The laterals from the cast iron shaft-piping at Butte are wrought iron—a combination that has also been used extensively in the Pennsylvania coal fields and in Europe.

Flange connections are generally used with the larger pipe sizes and with the rubber-lined pipe. Smaller lines usually are joined by some type of butt connector; threaded couplings causes turbulence and undue abrasion. Victaulic couplings are preferred at many mines, because less wear results and they are easy to break for inspection, to connect to different laterals, or to disconnect to unplug the line.

Valves are used sparingly, if at all. They wear rapidly and are always a possible cause of plugging in the line. The flow of pulp is usually directed from one line to another by reconnecting the lines. Where the pipeline is too heavy or rigidly held, disks are inserted in the line (as at Homestake) or valves may be necessary. Cone or plug valves are best; gate valves are nearly worthless. Any device for prohibiting the flow of pulp through a lateral must be located near the main line and not at the discharge end of the lateral.

Reductions in size along the line are common in the open-pipe systems. They are not common—indeed they defeat the purpose—in closed-pipe systems. Any but slight reduction or restriction may cause plugging in a finely adjusted, high pulp density, closed-pipe system.

Ninety-degree elbows are not used in pipelines for hydraulic filling; abrasion would be excessive. Curves of long radius are preferred, but a series of small-angle elbows is commonly used. Where space is limited, 90-degree turns have been made by using long-shanked,

Table 5. Details of some pumping plants

Location	Kind of pipe	Size of pipe (in inches)	Elevation head (in feet)	Horizontal distance (in feet)	Velocity (feet per second)	Percent solids	Dry tons per hours (average)	Screen analysis —200 (percent passing)	Gallons per minute (average)	Connected horse-power	Tonnage passed	Wear
Holden	wood	6	125	3,300	6-6.5	45-50	50	35	420	80	325,000	slight
Frood [a]	wood	6	[b]	2,000	[n]	60	125	20	310	[n]	[n]	[n]
Butte [a]	wood	8	[b]	variable	[n]	50-55	[n]	25	1,900	50	little	--
Mt. Lyell	steel	3½	819 [c]	10,700 [e]	6.7-8.3	47-55 [d]	28	39	[n]	460	500,000	1/16" maximum
Govt. Gold area [e]	concrete steel	8	45	11,000	[n]	50	500	[n]	[n]	[n]	932,000	negligible

[a] Discharge is open to air before entry into the gravity systems.
[b] Unknown but not great
[c] Maximum
[d] At stope—varies with location of stope; also varies along line because of "seal-water" additions.
[e] South Africa.
[n] Data not available.

rubber-lined tees. The sand in the stopped shank acts as a cushion for the impinging pulp. Other devices sometimes used at curves include rubber hose, lengths of curved, rubber-lined pipe, or renewable wear plates inside of the pipe.

Location and Layout of the Pipeline. The pipeline is ideally located where spills resulting from a broken line will not restrict the use of a shaft or drift, yet where it is easily accessible for repairs and unplugging. Practically, these conditions are rare.

Good alignment of the pipe with a minimum of irregularities promotes long life. This is increasingly important with higher velocities. A constant grade of the laterals is not necessary to flow of the pulp, but has occasionally proven helpful in reopening plugged lines.

No difficulty has been experienced in extending the discharge end of the line upward to reach stopes above the level of the lateral. Heights of more than 75 feet are common.

Operation of the Pipeline. Reliable operation of a pipeline used for hydraulic filling requires standardized procedures and constant vigilance against plugging and leakage. Other than by improper preparation of the pulp, plugging of the line may occasionally be caused by such things as the inadvertent operation of valves or blank disks, by allowing the discharge end of the line to become buried in the fill, or by improper flushing of the line. At all hydraulic-filling operations the line is flushed by clear water after running the pulp, and the admission of pulp is usually preceded by clear water. Plugging of the line is rare after the best operating conditions of a new system have once been determined and put into practice.

The location of plugs in a line can usually be found by tapping with a hammer. Unplugging necessitates opening the line at intervals and allowing the head of material behind the plug to force it out. The application of water or of water and compressed air is sometimes required. Air alone dries out the material and is not helpful. Wooden pipes are easily unplugged by boring holes and injecting water. The shorter the time a line is plugged, the easier it is to unplug.

A good communication system is an indispensible aid to smooth operation. Telephones are sometimes placed in the stopes to provide the quick communication necessary to minimize the effect of spills and to synchronize operations along the line.

Compressed air can be introduced into a pipeline as a means of increasing the effective radius of a system in which the head is limited, without diluting the pulp. This has been done at the Emma and Travonna sand-filling projects in Butte, at Hodbarrow, and at Mufulira. The air should be so injected that a stream of pulp is not directed against the opposite sidewall of the pipe. At Mufulira 72 cubic feet of air per ton of solids in a 4-inch line will extend the effective radius of the system 1200 feet.

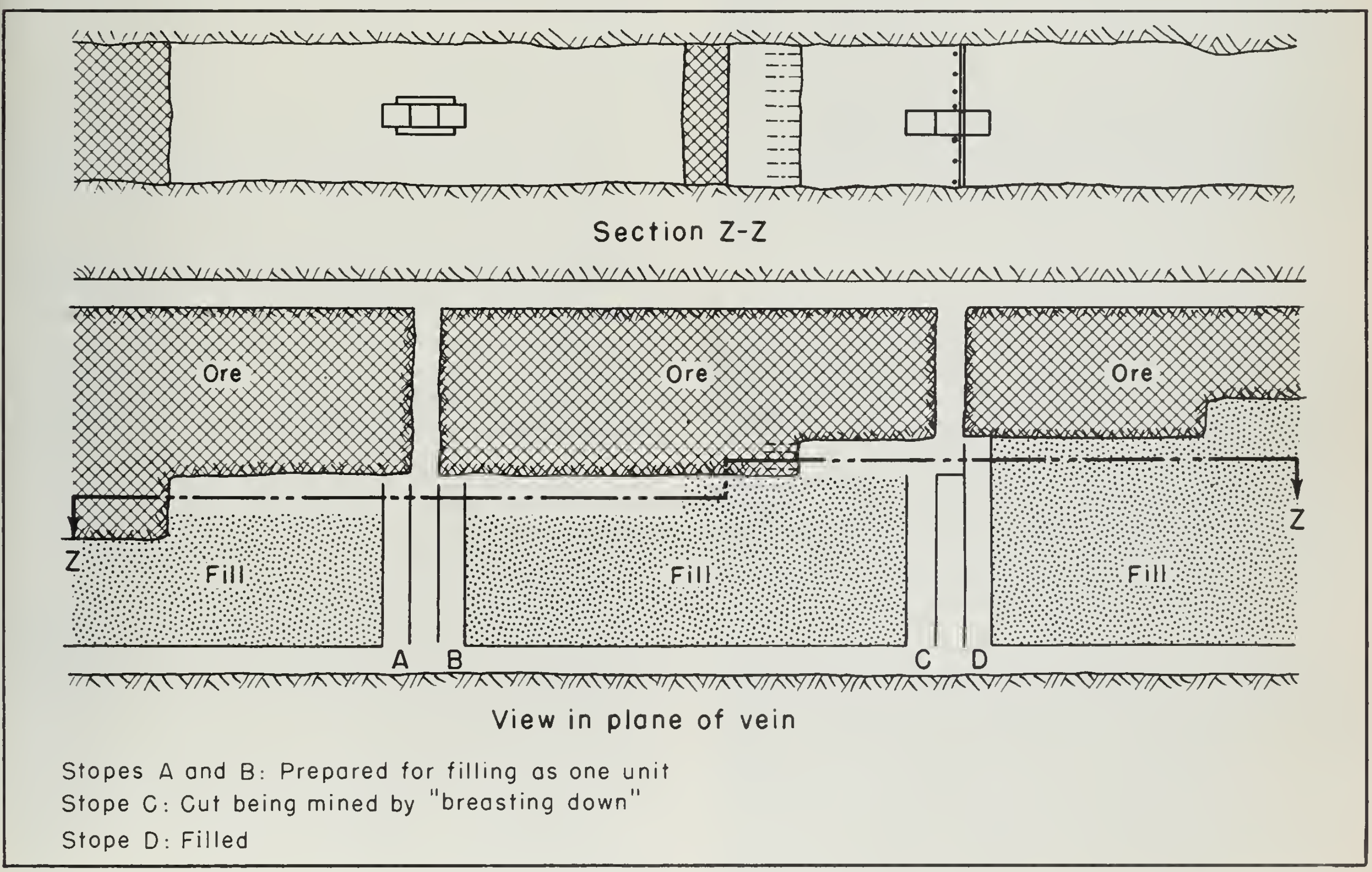

Figure 5. Horizontal cut-and-fill stoping. Filling to back.

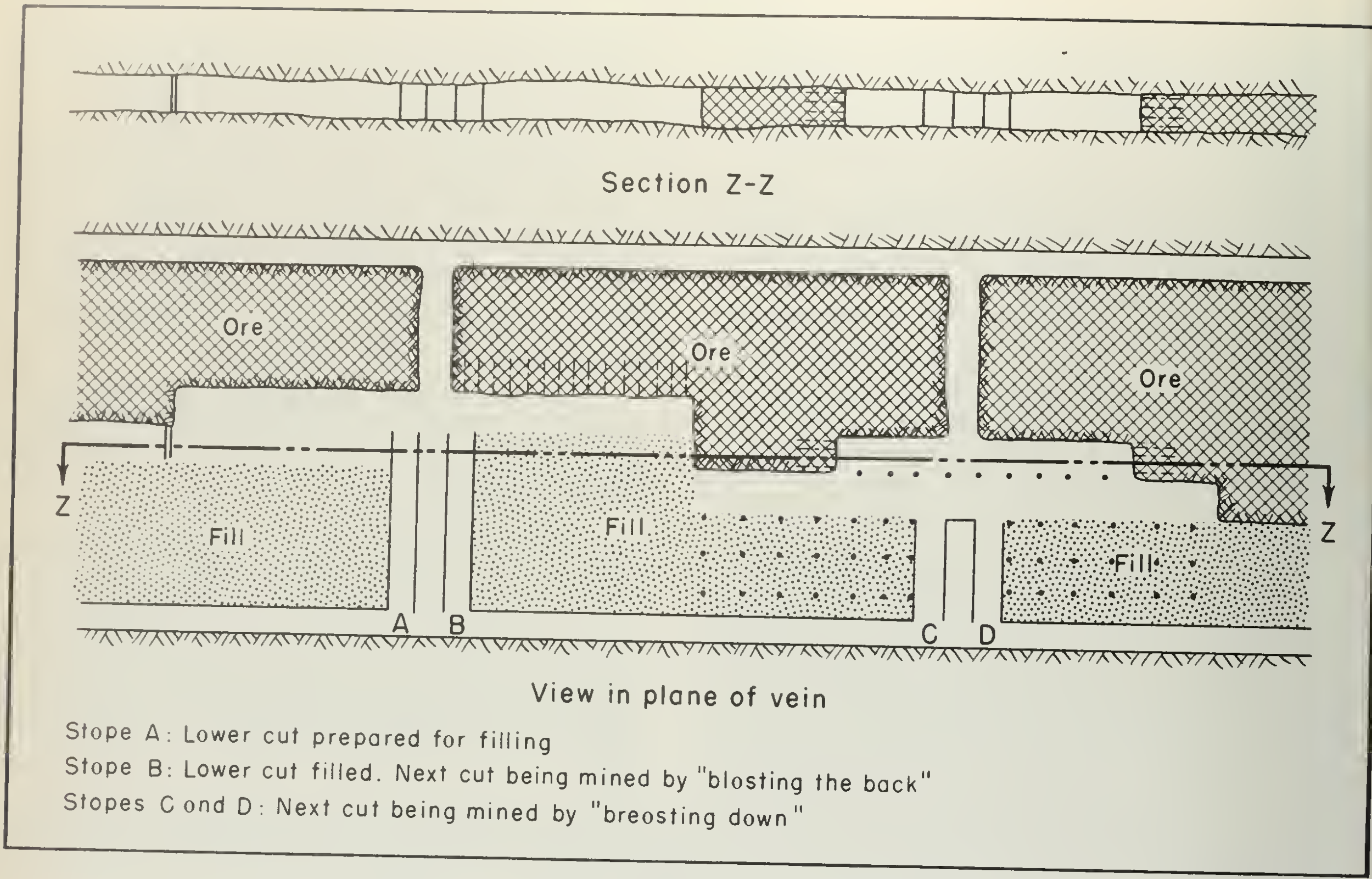

FIGURE 6. Horizontal cut-and-fill stoping. Two cuts open.

Boreholes. Boreholes have been used mostly at the mines on the Witwatersrand where they convey the pulp to the underground launder systems, and by suitable location eliminate the necessity of underground pumping. In other localities boreholes have found some use in connection with regular underground pipeline systems, or to introduce material into stopes.

Starting diameters of 4 to 12 inches are recorded, and depths are as great as 3600 feet. The boreholes in South Africa do not require lining. In other places, where the rock is friable, lining has been necessary. Reinforced concrete was used at Mufulira for lining after steel proved very short-lived.

In South Africa boreholes have passed large tonnages with no maintenance being required. They have the advantage that they do not disturb the shaft with breaks. However, unless they are large enough and in suitable ground, they are subject to plugging and may be expensive to reopen.

Launders. As an adjunct to hydraulic filling, launders have been used extensively only on the Witwatersrand. They are particularly adapted to certain mines on the Rand because of the moderate dip of the reef which allows the use of open fluming for underground distribution of the pulp. Launder installations on grades of more than 12 degrees are not uncommon, and on grades as high as 22 degrees have been satisfactory. At the outcrop mines, launders have been used for transportation of the pulp from the surface. At one property, for example, three launders averaging 12,000 feet in length are used to convey the pulp underground. These serve a front of 9000 feet along the strike. Such long launders have velocity breaks every 1500 or 2000 feet. Wood is usually used in construction of the launders, but concrete is sometimes used for lining. The amount of fines at the discharge end of long launders is noticeably increased over the amount at the feed end owing to abrasion enroute.

Where launders are used the pulp density must be kept below certain limits. Lower densities are required with flatter grades, more curves, larger particle size, rough launder surface, small volume, poorly shaped launder, or uneven grade.[30]

The advantage of pipe in controlling flow and reducting the hazard of spills precludes the use of launders in most metal mines.

Underground Practice

By proper preparation of the stopes, which consists essentially of good bulkhead construction, and suitable methods of dewatering, much is done toward assuring successful filling. The bulkheads contain the fill material within the stopes and also, in some circumstances, assist in dewatering. The kind of bulkheads that are constructed and the methods used for dewatering are therefore related, and they are determined chiefly by the size

[30] Caldecott, W. A., Sand and pulp table: Chem. Met. Min. Soc. South Africa Jour., vol. 15, p. 304, 1915.
Peele, Robert, "Sand filling" of stopes in metal mines: Mining Engineers' Handbook, vol. 1, 3rd ed., New York, John Wiley and Sons, Inc., sec. 10, art. 92, 1941. See also: sec. 10, art. 110.

and shape of a fill and by the characteristics of the fill material.

A fill may, in general, be dewatered by any one or a combination of three distinct means: by percolation, runoff, or decantation. Percolation implies eventual dissipation of the water either through filter-bulkheads or through fissures in the surrounding rock. The fill must be sufficiently permeable for quick draining where this method is used. Run-off is used to describe the methods in which a perforated drain-pipe or similar device extends upward through the fill and permits the continual draining of the water off the surface of the fill as the level of the fill rises. When a pool of water is allowed to collect on the surface of the fill while it is being placed the water may be decanted. Where draining is complete, or nearly so, by either of the last two methods, the bulkheads need not be of the filter type, but may be watertight.

If dewatering is accomplished by run-off or decantation, the settling rate of the material, the amount of surface area of the fill, and the rate of filling are important. The object is to maintain conditions that permit as clear an overflow as possible.

Flocculating agents have been added to pulps to assist in dewatering the fill and to cause the fill to consolidate more readily. Flocculation of the fill material may not always be an advantage, however, and thorough investigation and observation should attend its use until the effects are known. Contradictory results have been obtained at the New Brunswick and Central Eureka mines by the use of flocculation. At the New Brunswick mine, pressure on bulkheads was increased, although the fill was firm while being placed, and the practice was abandoned. At the Central Eureka, very light bulkheads are satisfactory, the fill sets well, and exceedingly clear water is decanted from the fills. At the Sliger mine also flocculation assisted dewatering and consolidation.

The possible effect of flocculation on subsequent metallurgy if some of the fill material is returned to the mill must not be overlooked. The use of flocculation in conjunction with hydraulic filling may be worthy of investigation at any mine where a very fine material must be used for filling.

Bulkheading is an inclusive term used for all the different devices that are constructed to contain the fill material. These devices may take the form of dams in restricted openings such as drifts, ore-passes, sub-levels, etc., they may resemble retaining walls and be used for holding the fill material within a limited section of a stope, or they may be merely a more elaborate lagging of the regular timber sets in the drift. The special lacing sometimes required around raises and chutes is also a part of the bulkheading. Any of these various forms of bulkhead may be constructed to permit water to filter through them, they may simply have drain pipes protruding through them, or they may be entirely watertight.

Wherever possible, bulkheads that are employed in connection with large fills should be placed away from direct vertical pressure. In smaller fills, especially those in which the width is not great, this is not important and, in fact, usually is not possible. When a fill is properly drained and consolidated the weight that must be carried by bulkheading beneath the fill is theoretically not great. Lateral pressures on the fill cause the weight of the fill to be taken principally by the wallrock so that only the bottom arch must be artificially supported. It is the unknown or uncertain condition within a fill that necessitates a large safety factor in the strength of bulkheads.

Experiments carried out on the tailing at Mufulira, as reported by A. C. Turton,[31] illustrate well the arching or doming properties of that material. A wooden box of 32 tons capacity was used in the experiments. For each succeeding test a square opening of 18 inches, 24 inches, and 36 inches was cut in the bottom. The tests consisted of introducing pulp of 68 percent solids into the box with the hole closed and lined with coconut matting. When the water content in the box decreased to 22 percent (about 90 minutes) the hole in the bottom was opened. During each test the material fell out to form a dome equal in height to 1.5 times the width of the opening. Following the last test the material was left exposed to the weather for 30 days, during which time 15 inches of rain fell. The dome remained the same, but there was considerable dripping from the bottom of the box.

Preparing stopes for filling and making bulkheads waterweight is not difficult, but requires careful work and usually requires close supervision in order to assure smooth operation.

Figure 7. Bulkhead construction in a raise in a narrow vein. The lagging is nailed against the raise timber and fitted roughly to the walls.

Fills of Small Volume per Pour. This group includes operations, as in cut-and-fill and some square-set mining, in which the volume of fill placed at any one time is small and the added increment of depth of fill for each additional pour is not great, being usually only 8 or 10 feet. Filling is required primarily to provide support of the stope during excavation of the ore and to permit mining of pillars. Commonly the vein dips steeply in these mines and the width may be as much as 30 feet or more. Figures 5 and 6 illustrate diagramatically some typical applications of hydraulic filling of this type.

The bulkheading required with this kind of filling may be divided into two classes: that which is used in the drifts and openings within or below the filled area and that which is used within the stopes to barricade off a certain portion of the stope or to prepare the chutes and manways for immersion in the fill. The timber used in a drift with hydraulic fill above does not have to be as

[31] Meem, J. C., Pressure, resistance, and stability of earth. Am. Soc. Civil Eng., Trans., vol. 70. pp. 352-358, 1910.
Turton, A. C., Sandfilling at Mufulira: Inst. Min. Met. Bull. 478, 24 pp., 1946; Discussion and reply Bull. 480, pp. 1-10, 1946.
Moulton, H. G., Earth and rock pressures. Am. Inst. Min. Eng. Trans., vol. 63, 1920.

heavy as that with waste fill above. Typical lagging of a drift is done with two layers of 2-inch planking at right angles to each other over the back of the drift, and one layer of planking behind the posts. Such timber is adequate for fills that ultimately extend more than 100 feet above the drift. No extra timbering is necessary just above the drift (sill set of the stope). Because the timber below a fill does not carry much of the dead weight of the fill, the pressure is heaviest during the first pour or two and thereafter usually does not increase. If the fill is not properly dewatered, however, excessive pressures may result and even very heavy timber may be inadequate.

At the New Brunswick mine, 10 by 10-inch posts are used with one layer of 3-inch lagging. During the first pour only, it is necessary to provide additional bracing of the posts. Thereafter, the fill is extended upward 140 feet without any additional pressure on this bulkhead. Here the lagging over the back was placed normal to the dip of the vein, but this is not always done.

The amount of bulkheading required in a stope depends on the width of the stope and the methods of stoping. If the vein is narrow, horizontal cuts are driven in both directions from the service raise. Ordinarily the only bulkheading then necessary is at the raises (fig. 6). When additional bulkheading is required in the stopes, as at the left end of stope A in figure 6, or at stope D in figure 5, 1-inch planking has proved satisfactory at several mines. These light bulkheads are easily constructed, and they may be removed after only a few days and the timber reused.

Watertight bulkheads are constructed by laying ordinary planks tightly together; tongue-and-groove boards are unnecessary in most cases. Leaks are calked with burlap, excelsior, or paper, or are battened over with odd pieces of wood. Similar methods are used where the bulkhead joins the walls. Where the bulkheads are constructed over a fill previously placed, they are sunk slightly into the fill. In critical locations that will be inaccessable during filling, concrete is sometimes employed in small quantities to assure thorough blocking of all possible leaks.

FIGURE 8. Surface of a hydraulic fill showing top of drainage launder and bulkhead construction. New Brunswick mine. This device is called a "mousetrap" by the miners.

FIGURE 9. Crib chutes calked with excelsior in preparation for filling. The fill is dewatered by decantation through the cracks between the cribbing.

Filter-bulkheads are constructed by allowing space between the lagging and providing a layer or filter media on the inside. Burlap or coconut matting is commonly used. Cinders, sand bags, linen cloth, hessian (an Australian product of sisal fibre), and used filter cloths have also been employed.

Dewatering of the shallow type of fills is accomplished by any of the three general methods. Where the fill is dewatered chiefly by percolation, filter-bulkheads must be constructed and the workings beneath the fill may become very wet. Where other methods of dewatering can be used, these disadvantages are eliminated, but preparations for draining are more elaborate.

Perforated drain pipes or special perforated closed launders are used in dewatering by the run-off method.

To dewater by decantation it is necessary to provide only some means of raising the level of the overflow as the level of the fill and the surface of the pond rise. The method chosen to accomplish this is commonly the simplest or most convenient, e.g., providing slots or chopping holes in the bulkheads and later closing them over, constructing the bulkhead as the level of the fill rises, plugging cracks between the planks in the bulkhead, adding the upward extension of a drainpipe, or plugging holes in a vertical drainpipe (see fig. 9).

The pulp is distributed in a stope from pipes, hoses, or launders. In general, it should be introduced as far from the drainage outlet as possible. Long stopes may necessitate occasional shifting of the pulp stream to prohibit segregation of the slimes. Where the stope is to be filled to the back, a light trestle must be erected to carry the pipeline to the far end of the stope.

At times during the filling operations some of the fill material may escape through fissures in the rock or through poorly calked bulkheads. This sometimes can be stopped by depositing the incoming pulp directly over

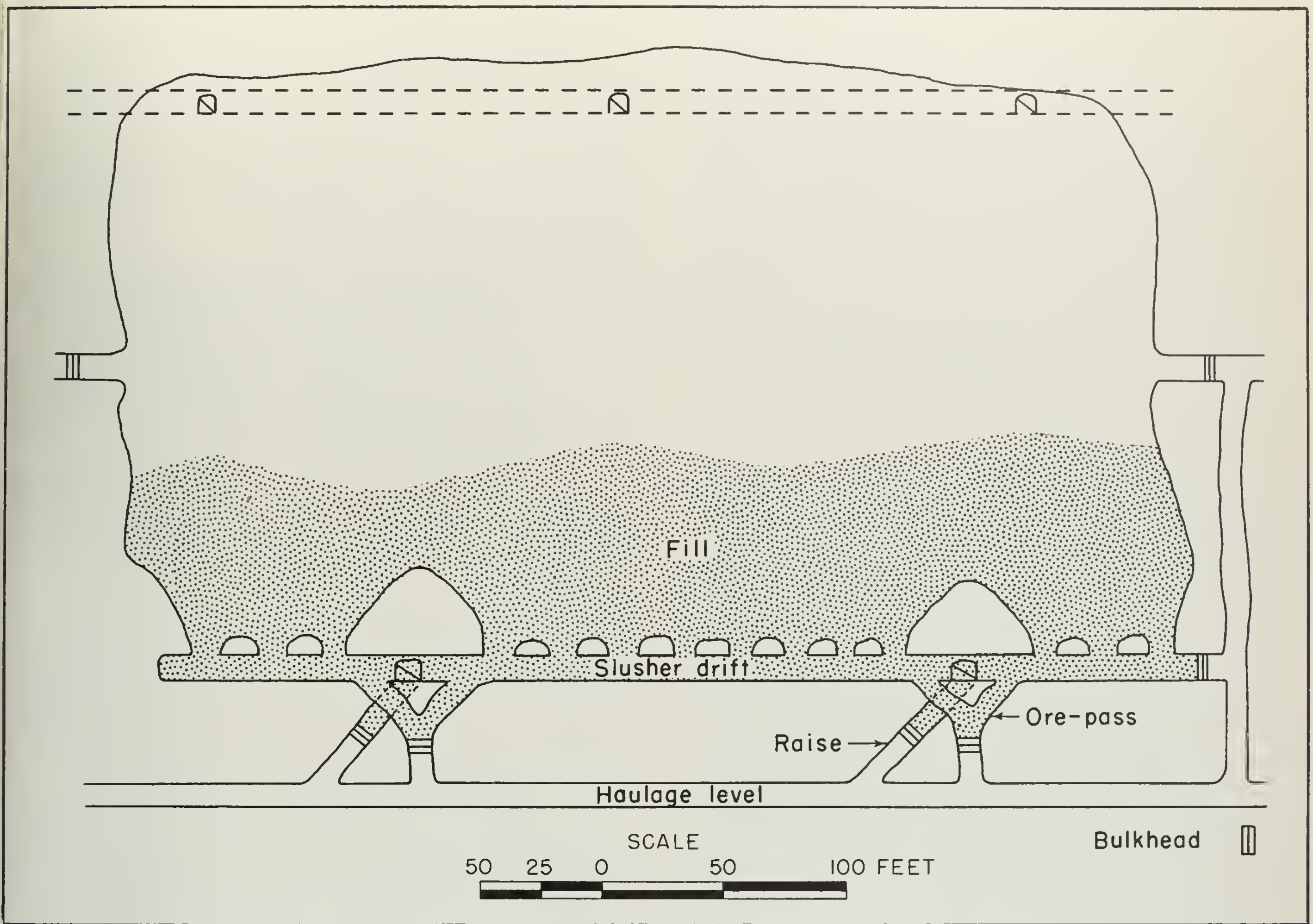

Figure 10. Typical open stope.

the point of leakage and providing special drainage away from the particular locality. The sands so deposited will usually form a filter and quickly stop further loss. Actually, the filling of fissures in the adjacent rock accounts for part of the effectiveness of hydraulic fills, and, if the fissures are not a part of an open system through which the material is conveyed to other workings, such filling is desirable.

Where the hanging wall is very badly broken an effective seal over a drift may necessitate leaving a small pillar. Recovery of such pillars was facilitated at the Sliger mine by the addition of Portland cement to the pulp that formed the first layer of fill placed above the pillar.

Hydraulic filling as applied in cut-and-fill stoping permits flexible mining operations. The fill may be raised to the back and the ore broken by breasting down or, if the ore is strong enough and the vein not too wide, the fill may be placed within 7 or 8 feet of the back and the whole cut mined by stoper drilling. Both of these methods have been used with outstanding results at mines in which square-setting had been required prior to the introduction of hydraulic filling. The ready availability of fill material in a mine equipped with a hydraulic filling system permits rapid and effective measures to be taken when changing conditions within the stope necessitate departures from routine stoping. Where hydraulic filling is used, the rate of mining is increased because of the rapidity with which fill material is deposited and because of the reduced amount of timber to be handled. However, filling usually interrupts the mining operation; ordinarily the mining is resumed the day following filling. Working on the fill during the same shift in which it is poured, however, is practiced at the Dayrock mine. Scrapers are commonly used directly on a hydraulic fill without laying floors.

Filling Large, Open Stopes. In some mines it is necessary to fill large, open stopes. Although the rock strength permits mining by open-stoping or by shrinking at these mines, the stope must finally be filled in order to assist the recovery of pillars, in the stabilization of the mine, or in the control of surface subsidence. Hydraulic filling has been beneficial in such mines. The bulkheads to contain the fill material are constructed in the drawpoints and in the sub-level entrances. Adequate dewatering of the fill to prevent excessive pressures is the most important consideration.

Sand filling was adapted at the Mufulira mine for support of the hanging wall in order to prevent flooding of the mine by caving into the overlying water-bearing formation, to prevent air blasts, and to attain predictable rates of ore extraction. The orebody consists of three superimposed, ore-bearing strata that range from 10 to 60 feet in thickness and are separated by a width of barren rock ranging from a knife edge to 50 feet. The strata dip 30 to 50 degrees. The sequence of stoping and filling is consistent with the modern theory of rock-pressure control, providing, in general, an advancing, arch-shaped stoping front followed by close filling. Stopes are opened up with a back of 350 feet down the dip, and have a strike width of 60 feet with 15-foot pillars between stopes. Tight filling to the highest part of the stope is not necessary, so the pulp is introduced only as high as is convenient in each stope.

Dewatering is accomplished principally by percolation, and therefore, although a considerable portion of the water is dissipated through fissures in the wall rock, the bulkheads must be of the filter type. The original bulkheads were wooden and consisted of 3-inch lagging placed with a 1-inch gap between pieces and supported on 9- by 9-inch timbers. The inside surface was covered with wire mesh and coconut matting. These bulkheads failed from concussion due to blasting in adjacent stopes.

Concrete bulkheads were next used. They were constructed 24 inches thick in the ore-chutes and 12 inches thick in the sub-levels and were reinforced with wire rope strung on hooks inserted in the rock. Drainage from behind the concrete bulkheads was provided by either of two means. Forty gallon oil drums were first used. They were perforated with 1-inch holes at 4-inch centers, wrapped in wire mesh and matting, and filled with rock, and fitted with a 2-inch pipe passing through the bulkhead. During World War II, when drums could not be obtained, a timber frame placed on the inside of the bulkhead and covered with wire mesh and coconut matting proved as effective,[32] although more susceptible to damage by falls of rock. In moving ground timber bulkheads are preferred unless the blasting is heavy.

The fill material is run into the stopes in batches of 700 to 1000 tons; 3 days are allowed between batches for percolation of the water and thorough setting of the fill. Supplementary dewatering is accomplished by decantation wherever sub-level access is available, but at no time is the pool of water on top of the fill allowed to exceed 3 feet in depth. Whenever filling is discontinued, within 6 hours the surface of the fill is dry and very compact. Drainage from the bottom of the fill ceases about 2 months after filling is complete. Bulkheads have been removed after allowing sufficient time for consolidation and the fill stands well, even though not cemented.

Hydraulic filling was a temporary expedient at Mufulira. It provided an economic and sufficient support for the extraction of ore without leaving large pillars and at the same time facilitated the drainage of the hanging-wall beds. Eventually conditions were improved enough to change to mining by caving methods. More than five million tons of hydraulic fill was deposited.

[32] A similar device employing burlap was unsuccessful at Homestake

The filling operations at Holden and Homestake also are of this type. At both of these mines fills of large volumes are deposited in a more or less continuous operation. In contrast to Mufulira, dewatering is done chiefly by decantation and secondarily by percolation; therefore, the bulkheads are constructed watertight, although they usually contain a drain pipe with a valve. The drain pipe provides for some dewatering, is helpful in estimating the condition of the fill, and provides a means of final drainage or drainage for stray water.

Most bulkheads at Holden are constructed of concrete, usually about 3 feet thick, are well hitched into the surrounding rock, and are reinforced with old drill steel. The pressure for which to design such bulkheads is one of the most enigmatic of hydraulic-filling problems. A liberal safety factor is always used. Shrinkage of the concrete sometimes causes leakage around the bulkheads, but this is stopped by gunniting.

The pulp is introduced into the stope from points near the back. Unless the discharge is shifted occasionally, cones of sand will build up and segregation of slimes results. Much of the water is drained off through fissures and cracks in the footwall, either from the pond on top of the fill or after some downward percolation through the fill. Wherever possible, water is decanted through the sub-levels. If the pool of water becomes too deep, a sinking-pump is lowered into the stope and is employed in decanting some of the water. A vertical drainage launder has been tried, but the long line and many curves caused the line to plug easily. Four months after completion of filling, only slight drainage was noticeable.

The fissures surrounding a fill serve effectively as a means of dewatering. When the fill material first enters a fissure in the country-rock, all sizes of particles go through. However, as the height of the fill is raised above the entrance to the fissure, the velocity of the stream is checked, which causes the sands to settle and act as a filter for the slimes. Thus the fissures are filled, in part at least, so that they contribute to the support of the mine and assist materially in dewatering the fill, or in removing other water.

At the Homestake mine the methods of mining involve two kinds of stopes that need different filling methods. The ore is localized along the minor folds that parallel the axis of the plunging anticline along which the folds occur. The orebody is mined by a series of vertical shrinkage stopes, 60 feet wide, alternating with pillars 40 feet wide. The long axis of the stopes and pillars is transverse to the axis of the anticline. The average elevation of each stope is less than the previous one as mining progresses downward along the length of the anticline. It is the shrinkage stopes that are considered here under the heading of filling large open stopes.

The vertical height of the ore usually exceeds 150 feet, which is the level-interval. To eliminate the necessity of a level-pillar, each stope is mined from the lower limit of the ore upward to a height 25 feet above the next level. After the ore is drawn, fill is deposited to the height of the level only, and as soon as it is sufficiently consolidated (about two weeks at least), a line of timber is constructed on the fill. Then the fill is carried to the back, some of the fill is drawn out to form hoppers above the

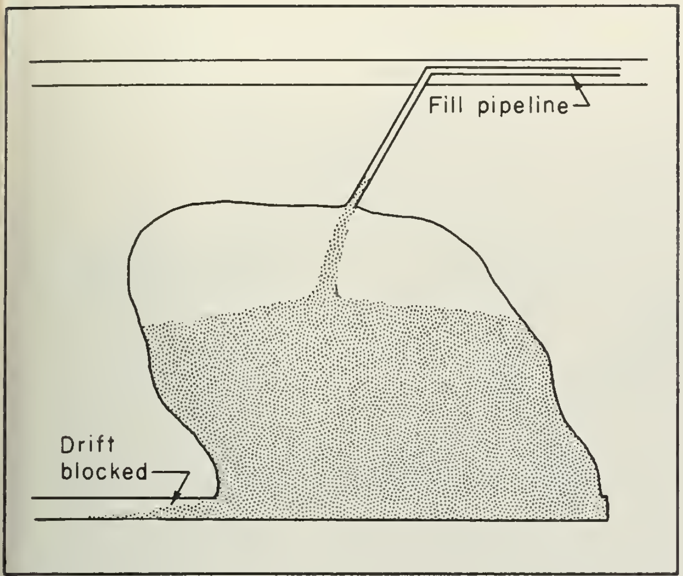

Figure 11. Effect of filling a stope without construction of bulkhead in adjoining drift.

chutes in the line of timber, and the stope is ready to shrink to the level above. Thus the shrinkage stopes, for the purposes of hydraulic-filling, are 60 feet wide, somewhat less than 150 feet high, and as much as 300 feet in length.

These stopes have sub-level access from the pillars at vertical intervals of 20 feet. These entrances, as well as the openings at the bottom, are closed by wooden bulkheads. A typical sub-level bulkhead is constructed of 12-by 12-inch timbers laid together horizontally and braced with a single vertical 12-by 12-inch timber at their centers. Each bulkhead is hitched in cement and covered with a layer of burlap to retain the fill material in case the timbers do not fit together well. A drain pipe and valve are usually provided. Wooden bulkheads are preferred to concrete because they are not as easily broken by moving ground.

Dewatering is accomplished chiefly by decantation at the sub-levels.

Several irregularities in past filling practice serve to illustrate the flexibility of these filling methods as employed at the Homestake mine. A fill has been deposited, owing to lack of sub-level openings, for a full height of 150 feet in a single operation without special provision for dewatering except by decantation on the top level. The fill apparently set as compactly as in better drained stopes. In dead-end stopes with no access above the level on which the ore was drawn, decantation pipes extending upward, one for half the height of the stope and the other for the full height, have been successfully used for dewatering. The more commonly used method, however, is to construct a timbered chimney which is an extension of a line of square-sets one above the other, and the whole enclosed with suitable lacing. The chimney is raised three sets at a time as the fill level rises. Continuous decantation is accomplished through slots in the lacing. This method provides good drainage and better observation of the fill, but may be dangerous unless the chimney is strongly constructed.

Another fill was deposited in a certain stope that would ordinarily require one bulkhead. However, no bulkhead at all was constructed (fig. 11). The fill material, introduced through the back of the stope, built up in the drift at an angle of repose of about 10 or 12 degrees until it blocked the drift. Thereafter, that block of fill material in the drift exerted the only constraining influence on the remainder of the fill, which was carried to a height of nearly 100 feet. Water filtered slowly through the fill into the drift.

Complete Filling of Parts of a Mine. Hydraulic filling has been used in some mines to fill completely certain parts of the mine. The pulp is introduced into the area at the bottom of the fill; or, as the fill progresses upward, at the lowest level at which the pulp will flow. Thus, the pulp, after being injected behind the bulkheads, flows upward through material already in place.

This method of filling has been used chiefly in fighting fires. It was used at Butte, Tintic, and Cerro de Pasco; it is now being used at Butte to prepare parts of the mines for mining by caving.

To prepare an area for filling, all entrances to the area are closed by suitable bulkheads. Figure 14 shows the kind of bulkheads constructed for this purpose at Butte and Cerro de Pasco

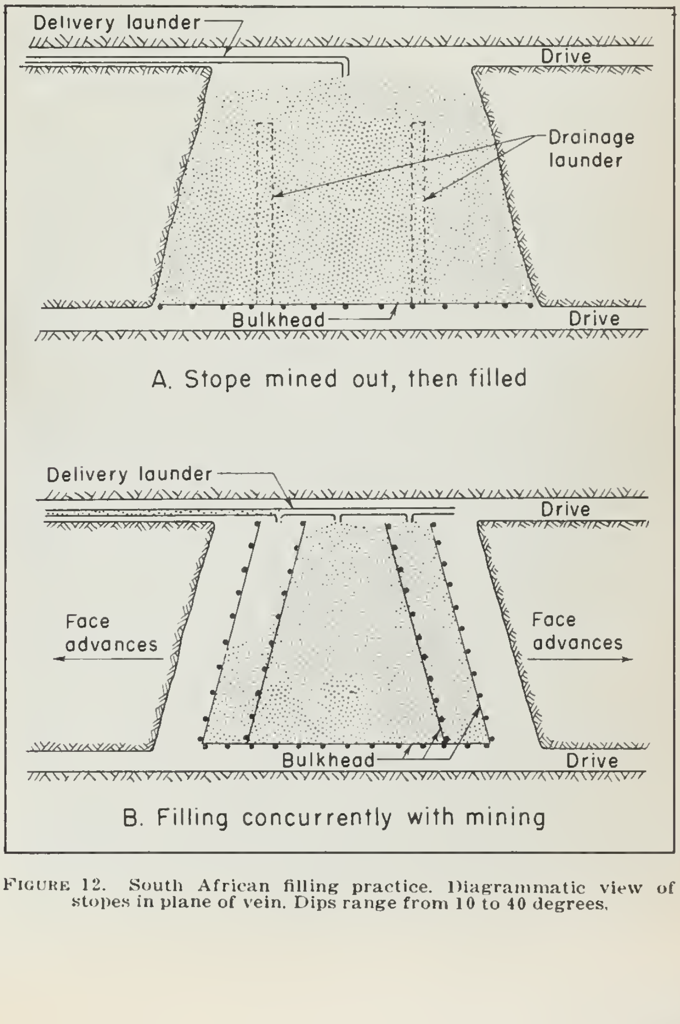

Figure 12. South African filling practice. Diagrammatic view of stopes in plane of vein. Dips range from 10 to 40 degrees.

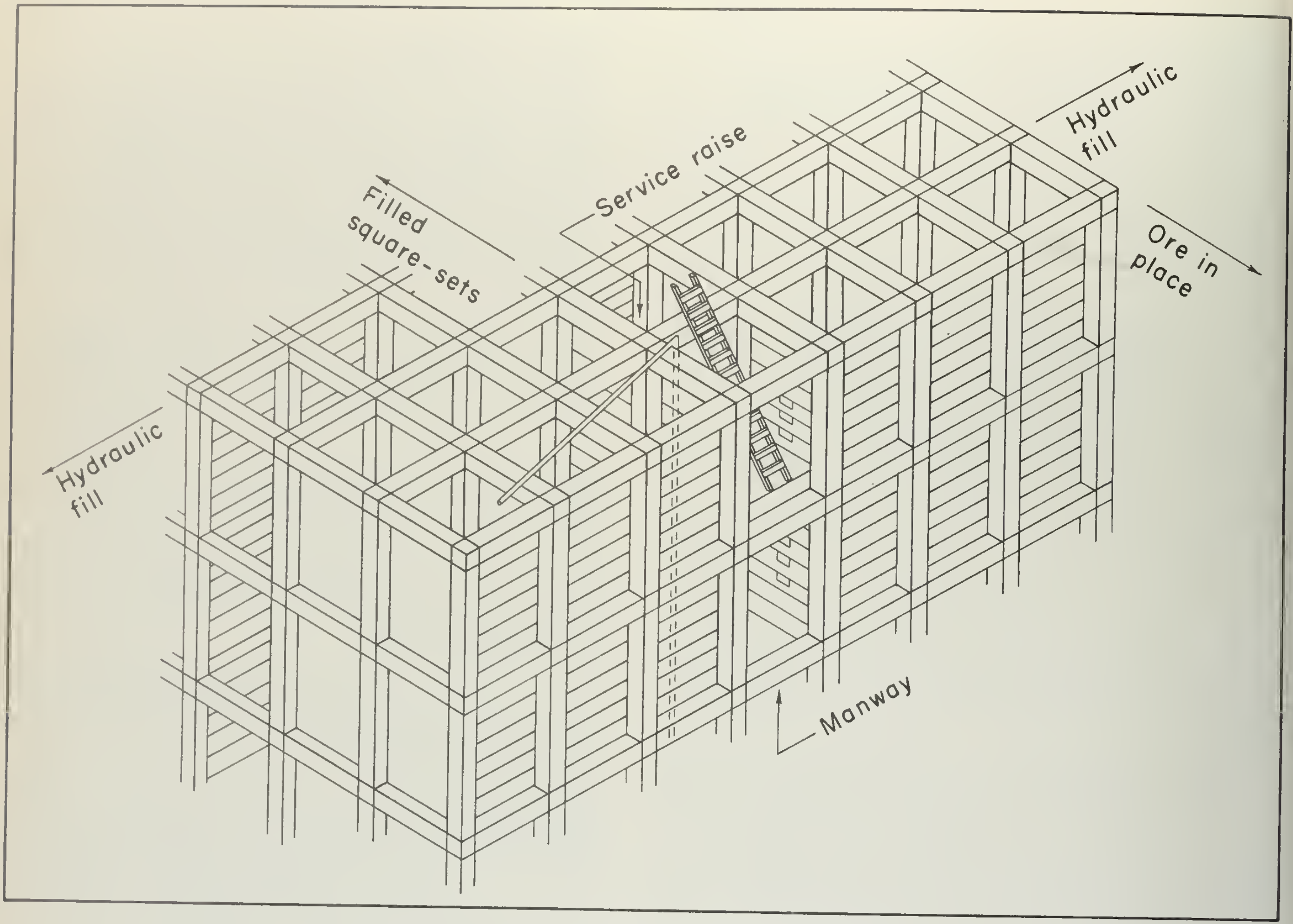

FIGURE 13. Square-set panel in pillar stope at Homestake.

Filling is begun at the lowest elevation in the area to be filled. The pulp is introduced through a bulkhead until the pulp no longer flows; it is then introduced through the next higher bulkhead. At Butte, material has been introduced into areas in which the level of the fill was 400 feet higher than the point of entrance of the pulp. Filling through any one bulkhead cannot be discontinued for too long a time or the fill behind the bulkhead will consolidate so as to prevent further filling. Experience has been contradictory as to the necessity for flushing the line after a "run". At the Central Eureka mine, whenever the discharge end is closed, the line plugs. This suggests that closed-pipe systems may not be suitable for use in filling operations of this kind.

No special provisions are made for dewatering, except a drain pipe through each bulkhead. Most of the water probably drains through the surrounding rock.

It has been reported that the fill material is kept slightly fluid during the period in which the fill is being placed, and therefore, all the cracks and crevices in the rock and in previously placed waste fill are completely filled; an effect that is very significant in fire fighting. A second important characteristic of this system of filling is that the fill is placed tightly against the back regardless of large differences in elevation along the back. Figure 15 illustrates the principle involved. If the pulp is introduced from above, it will not rise and fill cavities beyond a downward projecting obstruction, as in A. Where the pulp is introduced from below, as in B, the fill material carries upward directly to the back, and voids are left only where there is no escape for entrapped air.[33]

Other Examples of Hydraulic Filling Practices. The methods of hydraulic filling practiced on the Witwatersrand are unique among metal-mines. This is because of the low dip of the reefs and the relatively coarse nature of the fill material. Details of the many methods and modifications that are employed in hydraulic filling in South Africa are found in abundance in the technical literature. Only enough data are presented here to afford general comparisons with the methods that are more familiar in this country.

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[33] Hanson, Earl F., Control of underground mine fires at Tintic Standard mine: Am. Inst. Min. Met. Eng. Trans., vol. 126, 12 pp., 1937.

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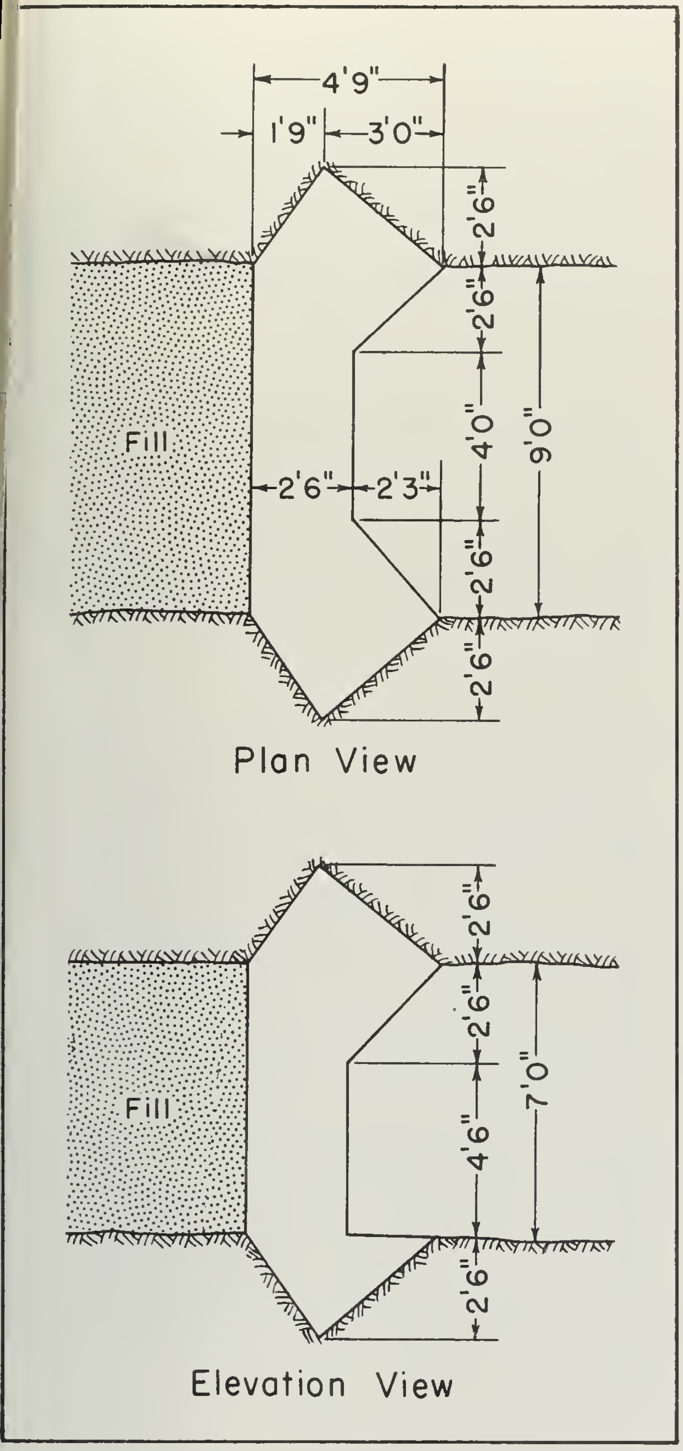

FIGURE 14. Concrete bulkhead.

Sand filling has long been used in South Africa for many purposes, including the recovery of pillars, the support of heavy ground during stoping, the support of overlying reefs, and the protection of shafts and drives. This discussion is confined to the filling methods used within the stopes.

The common method of mining is by advancing a long-wall face that is continuous between the drives. Figure 12 shows two such stopes. Hydraulic fills are employed either to fill mined-out stopes, as in A, or to provide support during current stoping, as in B. The predominant type of bulkheading consists of a row of vertical posts to which split lagging are attached horizontally. In addition, wire rope or a large-mesh wire screen is used to support a layer of coconut matting.[34] Other devices have been used for filtering and many variations have been described.

The pulp is distributed to the stopes by launders. Periods of filling in any particular stope are alternated with periods of draining. Dewatering is accomplished principally by percolation through the fill. Where the fill is bounded more by rock than by filter-bulkheads, drainage launders are sometimes used. These are simply ordinary launders covered with slats and coconut matting. As in other large fills, the location of the incoming pulp must be changed occasionally to prevent undue segregation.

Hydraulic filling has not been used on the Rand as much in the last couple of decades as it had previously. The average depth of mining is now great and not only the strength of the final support but also the time relations in placing it in position are important factors in determining the best kind of support to employ. The greatest disadvantage of hydraulic filling is that it is too cumbersome to handle close to the advancing, working face. The fill cannot be placed quickly enough nor cheaply enough. Other disadvantages that have been mentioned include the difficulty of maintaining supply lines of such great length, heavy pressures collapse bulkheads before fill can be placed, pumping costs increase with depth, amount of fines have increased in recent years, and the difficulty of transporting the large tonnage. According to Jeppe [35] the economic limit for hydraulic filling is 5000 feet of depth. It is generally agreed that the chief value of hydraulic filling on the Witwatersrand is in stoped-out areas in the shallower workings preparatory to mining of pillars or of hanging-wall reefs, and also for the protection of shafts and drives. Hydraulic filling is presently being used mostly on the Far East Rand (where the dip averages only 8 degrees), but there has been some revived interest throughout the Rand since the War.

As a final example of the variety and flexibility of hydraulic-filling methods, the system employed in mining the pillars at Homestake is illustrative. The pillars are vertical, tabular bodies, sometimes several hundred feet in length, about 300 feet in height, and 40 feet wide. They are bounded on both sides by the hydraulic fill previously placed in the former shrinkage stopes. The pillars are mined from the top down in successively lower lifts of 75 feet, by overhand, square-set stoping. The mining is accomplished by stoping out a series of panels, and filling each panel before mining the next. A panel is seven sets wide between the hydraulic fill on the sides, and only three sets wide along the long axis of the pillar. A panel therefore, is 75 feet high and only 7-by-3 sets in horizontal area. As a consequence of this method of mining, each panel of square-sets is mined upward to the full

[34] The bulkheads used at Hodbarrow and at the Emma and Travonna mines are similar, being wide-spaced lagging covered with burlap.

[35] Jeppe, C. B., Gold mining on the Witwatersrand: Transvaal Chamber of Mines, vol. 1, pp. 814-826, 1946.

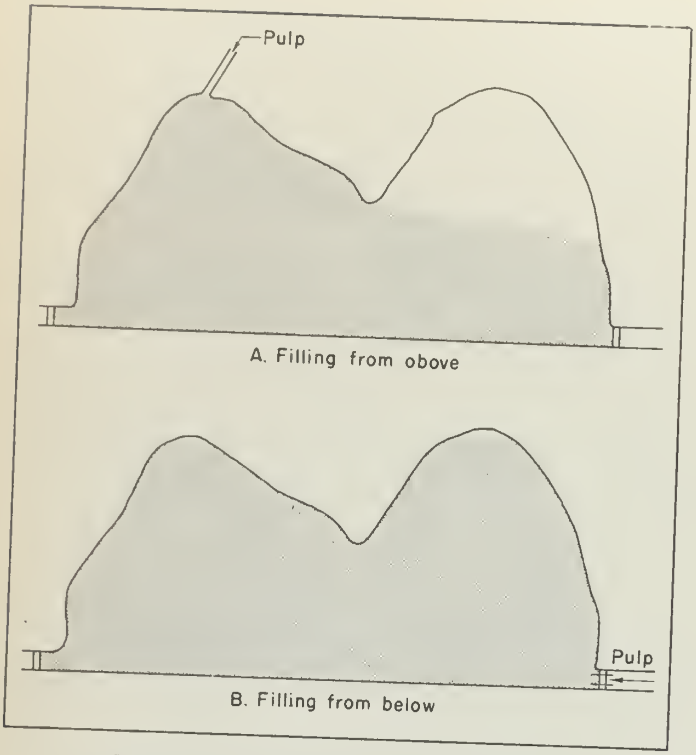

Figure 15. Filling against an irregular back.

height of 75 feet with hydraulic fill on three sides. Occasionally certain panels have been carried up with sand on all four sides.

Before filling a square-set panel the side that faces the unbroken ore is laced off with 4-inch tongue-and-groove lagging (fig. 13). The lacing is placed around two sets on the side adjoining the ore. This forms a manway for access during filling operations and subsequent mining of the next panel. In this manway the pipeline transporting the fill material is carried to the top of the panel. Also, on one side of the manway, the slots that are used for decantation during filling are exposed. The manway must be braced to insure safety to the operators during filling. Gunnite is used wherever necessary to seal cracks through which fill material might leak.

The discharge of the filling line is located so as to introduce the fill material as far from the decantation slots as possible. As the filling progresses water is decanted from successively higher slots and the lower ones are sealed by a board and a burlap gasket. About three runs of 700 tons each are required to fill a square set panel, and a day is allowed for setting between each run.

Handling Drainage Water. The amount of excess water introduced into the mine as a consequence of hydraulic filling is often not enough to cause any significant problem. For example, where the pulp is introduced at 70 percent solids and 10 or 15 percent moisture is retained in the fill, the increased mine drainage due to filling is not great. Several mines have found that hydraulic filling required no increased pumping capacity.

The water that drains from a fill sometimes contains as much as 10 percent solids, depending on the system used for dewatering and the amount of slimes in the fill material. By the time the water reaches the sump, it may or may not still carry the same amount of solids. Generally, enlarged settling chambers at the sump are constructed where hydraulic filling is employed, and the additional wear on pumps is not noticeable. It is not known that special solids handling pumps have ever been required because of hydraulic filling.

The water that drains from a fill commonly runs to the sump through the regular mine ditching system. Ordinarily the ditches must be of somewhat larger cross section than would otherwise be required and they must be mucked out more frequently.

At the Great Boulder mine a continuous system of piping throughout the height of the stoping section provides a direct pipeline all the way from the incoming main-line to the sump. The pipeline is broken at the stope to be filled, thereby depositing the fill material. The lower section of the same line is then used to carry off the drainage water. Dewatering is accomplished by decantation into this lower section of line. The advantages in keeping the mine clean are obvious, but the stopes must be conveniently located for this system to be used without much piping, and the preparations for dewatering may be complicated.

Operating Difficulties. Hydraulic filling has certain undesirable features, and some inconveniences and delays will probably always attend its use.

Besides pipeline troubles and the necessity for adequate preparation of stopes, occasional spills, which are evidently almost unavoidable, and increased sloppiness in openings below filled areas are the most troublesome consequences of hydraulic filling. The spills result from broken lines, broken bulkheads, and runs of material through fissures in the rock. Spills can sometimes be mucked by machine, but often hand mucking is required, which is a difficult job with the semi-drained, sticky material. Some operators suggest that a spare stope be kept in readiness below the stope being filled so that the pulp may be directed into it if trouble develops.

The degree to which a mine is wetter and muddier as a result of hydraulic filling depends in large part on the methods of dewatering. Collecting water by decanting or run-off and confining it in pipes or ditches is best. Where most of the dewatering is accomplished by percolation through the fill, control of the influx of water into lower workings is difficult. If the water is transported along the levels in ditches, accidental obstructions may dam the ditch causing overflow into the level, depositing slime.

Costs

Cost data for hydraulic filling are difficult to obtain and to correlate. Most published data are old and most unpublished data of present operations are restricted. Further, the figures that are available are seldom comparable because they differ in what they measure and are based on different units. The cost figures range within wide limits and only the most general conclusions are warranted.

The cost per ton of fill deposited at mines that place small fills is higher than at mines where fills of large volume are placed. The cost is lowest per ton where large

*Table 6. Costs of hydraulic filling**

Small fills		Large fills	
Date	Cost in dollars per ton	Date	Cost in dollars per ton
1938	0.89	1938	0.27
1943	0.71	1944	0.11
1944	0.42		
1949	0.33		
1948	0.32		
1934	0.29		
1945	0.26		
1930	0.25		
1937	0.24		
1946	0.20		

* These costs are each from a different mine. The year is given to establish the general level of economic conditions at the time. The costs are per ton of dry fill deposited.
The figures from foreign operations have been recomputed at the official exchange rate for the country and date.

volumes are handled, a minimum of bulkheading is necessary, gravity handling is employed, the system is run as nearly continuously as possible, current mill tailing is used, and the depth is not excessive.

Direct Costs. The costs of hydraulic filling include labor, materials and supplies, capital investment and maintenance, and power or fuel. The labor involved in hydraulic filling accounted for more than 40 percent of the total cost at each of the mines investigated; it accounted for more than 50 percent at a majority of them. Labor charges chiefly originate from surface plant operation, pipeline patrol, bulkhead construction, stope filling attention, and ditch maintenance.

The labor required at the surface depends on the type of equipment that must be operated. All plants must have a man readily available during the filling period in case of emergency shutdown, and most plants require the attention of one or two men continually for regular operation. The New Brunswick strict-batch agitation plant requires attention only toward the end of the period during which it is being filled and during the mixing period prior to discharge of the tank. Most other agitator plants require some attention during the complete cycle.

A pipeline patrol is maintained at two mines where abrasion has caused frequent leaks, but wherever pipeline leakage is less common and where a suitable communication system is in use such a patrol is not used. This cost, therefore, is applicable only in certain mines.

Stope preparation, including bulkhead construction, is often the largest single labor expense, being frequently over half of the total cost for labor. Customarily, special crews perform all the work of preparing the stopes.

The smaller type of fills require one or two men in the stope to control dewatering, guard against leaks, shift the discharge occasionally, and watch the general progress of the fill. Larger fills do not require constant attention in the stope, but do require constant patrol of the area surrounding the fill and of bulkheads for the discovery of spills, leaks, or weak structures.

Increased mucking of ditches and spills was shown to be one of the consequences of hydraulic filling. The charges involved in this are sometimes a substantial part of the labor cost.

The second largest portion of the cost of hydraulic filling is usually for the materials and supplies required. Most of this is for material used in bulkhead construction and in sealing the stopes or constructing filtering devices, e.g., matting, burlap, wire mesh, excelsior, cement, etc.; other minor costs are for miscellaneous items such as flocculating agents and lubricants. Because of the cost of burlap and some of the other filtering media, methods of dewatering in which they are not used are sometimes preferable, especially in this country. For example, the Homestake mine has reduced the cost of filling the square-set, pillar stopes by substituting tongue-and-groove lacing for flat-edged planking and burlap.

The cost of power that may be charged to hydraulic filling is, in none of the mines for which data are available, more than 25 percent of the total cost; it is usually less than 15 percent. This includes the power required in returning the excess water to the surface.

The costs for equipment, installation, and maintenance, or the capital charges for these, have been reported, if at all, in such widely differing units that correlation is impossible. The two principal items of capital investment are the preparation plant and the equipment needed for transporting the pulp. The preparation plant, depending mostly on the type of plant and whether it can be constructed locally, may constitute anything from a very small part to a very large part of the capital investment. The cost of the transportation system can be calculated for any given property quite accurately. The greatest saving to be investigated is in the use of ordinary steel pipe in lieu of rubber-lined pipe. The cost of installing the pipeline may be considerable, especially where large pipe is used and where elaborate precautions must be taken against vibration of the line. The 300-ton plant at the New Brunswick mine is a notable example of low capital investment for an effective plant. The construction and installation of both the preparation plant and the pipeline is reported to have cost only $7000.00.[36]

The cost of hydraulic filling at several different mines, together with the year in which these costs were incurred, are given in table 6. Costs at some of these mines, as at the Homestake, have undoubtedly been somewhat reduced since the original figures were obtained.

Comparative Costs. A comparison of the cost of hydraulic filling with the cost of another method of filling at the same mine could be an illustration of the economy of hydraulic filling; however, only meager data are available.

Prior to the use of hydraulic filling at the Sligar mine, the cost of filling equalled the cost of mining the ore. Specific costs of the hydraulic filling are not disclosed, but listed among the economies claimed are a 50 percent reduction in timber consumption and a reduction in the number of men used in filling from more than 20 to three.

At the Matahambre mine the direct cost of filling was reduced from 55 cents to 29 cents per ton of fill placed. Total savings were about one dollar per ton of ore mined.

At the South Mine, Broken Hill, costs of filling were reduced during the war years and the following period of rising wages by the introduction of hydraulic filling in place of mechanically-handled sand or of waste fill.

[36] Krebs, Richard, and O'Donnell, J. C., Sand-slime stope filling proves satisfactory: Eng. and Min. Jour., vol. 150, no. 1, pp. 54-60, 1949.

The cost of prewar filling methods was prohibitive at the New Brunswick mine in the period following the war, but the introduction of hydraulic filling permitted the resumption of mining operations.

At the Central Eureka mine, mining would not have been possible following the war without the economy of hydraulic filling, which has kept the costs of mining at nearly the pre-war level. The cost of labor of filling in 1939, when waste rock was used, was nearly twice the total cost of filling in 1949.

Hydraulic filling has been employed in some mines regardless of cost because of development, general mine maintenance, and tailing disposal, sometimes indicates that hydraulic filling is the most economical method although the direct filling costs per ton of fill may show no increase.

Hydraulic filling, speaking broadly, is different in every application. Basic principles are the same, but modifications of the methods employed are common and consequently, details of practice vary considerably. The physical layout of the mine and particularly the character of the material utilized for filling are of paramount importance in determining the best practice. Some preliminary experiments on the consolidation properties of the material and on the other aspects of the system prior to introduction of large-scale hydraulic filling has proved advisable. The variations and modifications possible, both in the technique of filling and in other phases of mining, are innumerable.

Table 7. Metal mines employing hydraulic filling.

Butte, Montana, Anaconda Copper Company: for fire fighting and fire prevention; Emma and Travonna mines; Greater Butte project.

Central Eureka mine, Central Eureka Mining Company, Sutter Creek, California.

Cerro de Pasco, Peru, Cerro de Pasco Copper Corporation.

Dayrock mine, Dayrock Mines Incorporated, Wallace, Idaho.

Frood-Stobie mine; International Nickel Company of Canada, Limited, Copper Cliff, Ontario.

Great Boulder mine, Great Boulder Proprietary Gold Mines, Limited, Finiston, West Australia.

Hodbarrow mines, Hodbarrow Mining Company, Limited, Millon, Great Britain. Not operating at present.

Holden mine, Hose Sound Company, Chelan Division, Holden, Washington.

Homestake mine, Homestake Mining Company, Lead, South Dakota.

Matahambre mine, Minas de Matahambre, Matahambre, Pinar del Rio, Cuba.

Mount Lyell, Tasmania, Mount Lyell Mining and Railway Company, Limited: Royal Tharsis mine; North Lyell mine; Crown Lyell mine.

Mufulira mine, Mufulira Copper Mines, Limited, Mufulira, Northern Rodesia.

New Brunswick mine, Idaho-Maryland Mines Corporation, Grass Valley, California.

Philippeville iron mines, Philippeville, Algeria.

Sliger mine, Middle Fork Gold Mining Company, Georgetown, California. Mining has not been resumed since the war.

South mine, Broken Hill South Limited, Broken Hill, New South Wales.

Triton mine, Reedy, West Australia. Not operating.

United Verde mine, Phelps Dodge Corporation, Jerome, Arizona.

Witwatersrand, South Africa, many mines.

Although some other method of filling may be preferable at some mines, hydraulic filling has wide application for many kinds of mining and for many different purposes. It has been used in coal mining, ferrous and non-ferrous metal mining, and undoubtedly could be employed in the mining of nonmetallics. It has been used in steep veins, narrow seams, wide lodes, massive ore bodies and in bedded deposits. It has been used in conjunction with current mining, in preparation for future mining in the rehabilitation of old workings, and in a host of other ways as an adjunct to mining. Apparently no hydraulic-filling operation connected with metal mining has ever been unsuccessful, either technically or economically.

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